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(54) Title: HIGHER-ORDER-MODE DISPERSION COMPENSATING PHOTONIC CRYSTAL FIBRES

(57) Abstract: The present invention relates to a novel group of cladding and core designs, especially for use in optical fibres, which provides enhanced dispersion properties through waveguiding of higher-order modes. In a first aspect, the present invention relates to an optical fibre with a waveguide structure for supporting the transmission of light at a predetermined or operating wavelength λ_0, said optical fibre having a longitudinal direction and a cross-section perpendicular to said longitudinal direction, said optical fibre comprising: a central region (41) having a centre axis in said longitudinal direction, said central region extending along and including said centre axis, said central region having an outer periphery with a maximum distance to the centre axis $r_{centre,max}$, a minimum refractive index $n_{centre,min}$, an effective refractive index $n_{centre,eff}$ and/or a resultant geometrical index $n_{g,centre}$, a core region (43) extending along said longitudinal direction and surrounding said central region (41), said core region having an inner periphery that coincides with the outer periphery of the central region, an outer periphery with a maximum distance to the centre axis $r_{core,max}$, a maximum refractive index $n_{core,max}$, an effective refractive index $n_{core,eff}$ and/or a resultant geometrical index $n_{g,core}$, a cladding region (45, 46) extending along said longitudinal direction, said cladding region surrounding and neighbouring said core region (43), said cladding region having an inner periphery that coincides with the outer periphery of the core region, an outer periphery with a maximum distance to a centre axis $r_{cladding,max}$, a maximum refractive index $n_{clad,max}$, an effective refractive index $n_{clad,eff}$ and/or a resultant geometrical index $n_{g,clad}$. Here, it is preferred that $n_{centre,eff}$ is equal to or lower than $n_{clad,eff}$ and $n_{clad,eff}$ is lower than $n_{core,eff}$ at the wavelength λ_0, and/or it is preferred that $n_{g,centre}$ is equal to or lower than $n_{g,clad}$ and $n_{g,clad}$ is lower than $n_{g,core}$ at the wavelength λ_0. In preferred embodiments, the core region and/or the cladding region comprise (micro-)structural features. The invention further relates to a dispersion compensating module comprising and a preform for producing said optical fibres. The invention may e.g. find applications in high capacity, high transmission rate optical communications systems, e.g. WDM-systems.

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HIGHER-ORDER-MODE DISPERSION-COMPENSATING PHOTONIC CRYSTAL FIBRES

FIELD OF INVENTION

The present invention relates to a novel group of cladding and core designs, especially for use in optical fibres, which provides enhanced dispersion properties through waveguiding of higher-order modes.

BACKGROUND OF THE INVENTION

The development of optical amplifiers operating in the 1550 nm wavelength band of optical communication have during the past ten years formed the basis for a tremendous development of wavelength division multiplexed optical communication systems typically operating in the wavelength interval from 1530 nm to 1610 nm - and rapidly expanding. These amplifiers have to a large degree removed the loss limitations of the optical communication links, and have paved the way for much longer transmission spans operating at significantly higher transmission bit rates (having a much higher transmission capacity). At the same time the development of optical fibre amplifiers at first had the result that systems originally developed to operate in the 1310 nm wavelength band could be upgraded to the 1550 nm band with significant advantages – provided that the dispersion limitations of these systems could be compensated in an efficient manner. In further steps much more detailed schemes for dispersion management have been developed, and numerous techniques have been developed.

To provide a picture of the possibilities and needs, it may be noted that when the bit rate is increased to 10 Gbit/s, the dispersion limits the transmission to around 50 km, which obviously raises the need for some sort of dispersion compensation. As described by Grüner-Nielsen et al., ECOC´2000 pp.91-94, non-zero dispersion fibres (NZDF) seems to be the choice for future communication systems due to their low-dispersion and low-non-linear penalties. For bit-rates of 10 Gbit/s NZDFs will not need dispersion compensation before some hundred kilometres of transmission. However, in

the future, when the bit rates increase to 40 Gbit/s, dispersion compensation will be needed already after approximately 5 kilometres for non-shifted fibres and after around 30 kilometres when NZDFs are used.

It is noteworthy that today several different types of optical transmission fibre is installed with various dispersion properties. However, still a significant part of the installed optical fibre cables make use of non-shifted single-mode fibres, i.e., optical fibres with zero dispersion wavelength at 1310 nm and a dispersion of about 17 ps/km/nm at the wavelength of 1550 nm. The most established dispersion-compensation method today is the use of dispersion compensating fibres (DCFs) operating in the single-mode regime. The use of dispersion compensating fibres was proposed by Lin, Kogelnik, and Cohen, Optics Letters, Vol.5, No.11, 1980.

It is a disadvantage of the dispersion compensating fibres using standard fibre fabrication techniques (i.e., fibres fabricated from doped silica) that limited dopant levels (given by internal stress, material deposition efficiencies etc.) does not provide as large (negative) dispersion values as other competing techniques. It is a further disadvantage that standard single-mode DCFs typically have significantly smaller spotsize values than the transmission fibres, whose dispersion they are to compensate. The spotsize mismatch generally leads to significant coupling losses, and/or complicated splicing techniques including intermediate fibres, special techniques of material diffusion control etc.

Another very interesting dispersion equalization techniques was suggested by Poole, Nelson, Wiesenfield, and McCormick, Optics letters, Vol.17, p.985, 1992. The described method was based on the principle of converting the LP_{01} mode (linearly polarised mode of lowest order) from the communication fibre to a LP_{11} mode (linearly polarised mode of higher order with an azimuthal cosine shaped field variation) in a compensating fibre, and using the high negative dispersion of the LP_{11} mode close to its cutoff wavelength to compensate for the dispersion in the communications fibre. The advantage of using higher-order mode dispersion in standard optical fibres is that compared to fundamental mode dispersion compensation, the higher-order mode (HOM) DCFs may provide a larger negative dispersion. The cost of obtaining this stronger dispersion compensating capability per unit length of fibre is, however, the

necessity to perform a mode conversion from the light emerging from the single mode transmission fibre in the LP_{01} spatial mode to the LP_{11} mode (as originally suggested by Poole et al.). DCFs which also operate by guiding the LP_{02} mode (as disclosed by Vengsarkar and Walker in United States Patent no. US5,448,674) have also been proposed. Several design approaches have been described for HOM-DCFs using standard fibre technology, including design spaces for obtaining more robust dispersion compensation values with regard to fibre parameter variation (see e.g., Vengsarkar, and Wagener United States Patent no. US5,802,234).

It is a disadvantage of the known HOM-DCF fibres that the fibre designs generally allow the fundamental mode of the optical fibre (the LP_{01} mode) to be even better guided (with lower propagation losses) than the desired higher-order modes. If not a completely efficient mode conversion is made at the input end of the DCF, the fundamental mode will be relatively stronger represented at the output end of the DCF, leading to decreased signal-to-noise ratio.

It is a further disadvantage of the HOM-DCFs realised by standard fibre technology that the relatively limited dopant levels put significant restraints on the maximal refractive index difference and thereby the maximum dispersion compensation.

Recently a new type of optical fibre that is characterized by a so-called microstructure has been demonstrated. Optical fibres of this type (which are referred to by several names – e.g., microstructured fibres, photonic crystal fibres, holey fibres, or photonic bandgap fibres) have been described in a number of references, such as WO 99/64903, WO 99/64904, and Broeng et al. (see Pure and Applied Optics, pp.477-482, 1999) describing such fibres having claddings defining photonic band gap (PBG) structures, and United States Patent no. US5,802,236, Knight et al. (see J. Opt. Soc. Am. A, Vol.15, No.3, pp.748-752, 1998), Monro et al. (see Optics Letters, Vol.25 (4), pp.206-208, 2000) defining fibres where the light is transmitted using modified total internal reflection (M-TIR). This invention concerns in first aspects mainly fibres that are guiding by M-TIR, but also PBG guiding fibres are addressed in aspects of the invention.

Photonic crystal fibres (PCFs) are known to exhibit waveguiding properties that are unattainable using conventional fibres. One of these unique properties is the ability that the wavelength-scale microstructured sections of the PCF in practice act as an "artificial" material with specially designed and much stronger spectral flexibility than obtainable by any homogeneous materials. This completely new design possibility for PCFs compared to standard optical fibres provides a wide range of new functionalities, such as for example the so-called endlessly single-mode fibre as described by Birks et al., Optics Letters., Vol.22, (13), July 1997.

As disclosed by DiGiovanni et al. in US5,802,236 (or EP0810453), a significant aspect of the design of the microstructured DCF is its ability to yield large effective index differences (exemplarily > 10% and more) allowing for relatively short lengths of microstructured DCF to be able to compensate dispersion of the transmission fibre in an optical communication system.

In patent application WO 00/55661, optical fibres are disclosed, in which the core contains a central segment being a void. The fibres described in WO 00/55661 are aimed at reducing non-linear effects and being particularly suited to transmission of high power (typically >10 mW), multiplexed signals over long distances (> 100 km) without regeneration. For this reason, the preferred fibre design according to WO 00/55661 has a relatively large effective area and a low dispersion slope. The central-void designs presented in WO 00/55661 presents radii and relative indices of the segments, which provide an effective area greater than about 70 μm^2 and a dispersion slope less than about 0.08 $ps/km/nm^2$. Central embodiments of the fibre designs are characterized by zero dispersion wavelengths in the range of about 1450 nm to 1650 nm. All fibre designs in WO 00/55661 are described as having a central void and one or more (typically three) annular, concentric and solid segments that surround the central void.

It is important to notice that all of the central-void structured fibres, which have been demonstrated in WO 00/55661, are fabricated using doped and un-doped silica glass for obtaining the annular segments surrounding the central void of the fibre. Relative index values are ranged from −0.3% to 1.1%.

It is a disadvantage of the fibre designs presented in WO 00/55661 that they solely address the single-mode property of the waveguides. This is a particular disadvantage since the fundamental mode of single-mode fibres generally has a significant strength of the electromagnetic field in the central part of the fibre. When the objective, therefore, is to obtain a large effective mode-field area, it is unavoidable that the mode-field will be centrally deformed, and moreover that the propagation properties of the fundamental mode will be hampered by the central void.

In view of the considerable technical and commercial perspectives of dispersion compensation in optical communication systems, it is clear to those skilled in the art that a technique that avoids or at least mitigates the shortcomings of prior art DC techniques would be highly desirable. This application discloses such a technique, and articles that embody the inventive technique.

It is an object of the present invention to provide a new class of optical waveguides, in which the refractive index distribution is especially suited for guiding of higher-order fibre modes. These designs are primarily aimed at higher order modes corresponding to LP_{11}-modes in standard optical fibres, but the outlined design strategy is not limited to these modes and may be used to obtain improved propagation properties of other higher-order modes.

It is a further object of the present invention to provide optimised fibre parameters, for the realisation of higher-order mode dispersion compensating photonic crystal fibres.

It is a still further object of the present invention to provide designs for improved connection and splicing to standard optical fibres to the photonic crystal fibres covered by the invention.

It is a still further object of the present invention to provide optical fibres exhibiting new properties facilitating efficient mode conversion between fundamental and higher-order modes.

It is a still further object of the present invention to provide fibre waveguide structures, which are easy to manufacture.

GLOSSARY AND DEFINITIONS:

In the present application the terms photonic crystal fibres (PCF) and microstructured fibres are used interchangeably for optical waveguides for guiding light comprising so-called microstructures in the cladding and/or core regions. In general the fibres have a longitudinal direction (also termed 'axial direction') defined bv the direction of light guidance. The term 'elements' is in the present application used interchangeably with microstructures for features in the fibre that appear in a background material e.g. 'cladding elements' are structural features in a cladding region, where the elements differ from the background material in that they are composed of another material and/or have a different refractive index or spatial index distribution. The terms 'refractive index' and 'index' are used interchangeably. The term 'refractive index profile' refers to the spatial variation of the refractive index, typically related to a radial dependence of the refractive index in a cross-section of the fibre perpendicular to its longitudinal direction.

In the present context the terms 'fundamental mode' and 'higher order modes' refer to field solutions of Maxwell's equations for propagation of electromagnetic waves in a guiding system, in particular such solutions that fulfill the boundary conditions imposed by the waveguide in question, a 'fundamental mode' being characterized in that it shows no variation in one of the directions of the chosen coordinate system in a cross section of the waveguide (i.e. azimuthally or radially in a circular waveguide). The fundamental (or dominant) mode is the mode having the lowest cut-off frequency for the waveguide configuration in question. In a circular optical waveguide the fundamental mode is termed LP_{01} representing a linearly polarized mode with no field variation in the azimuthal direction of a circular waveguide. Higher order modes are termed LP_{nl}, $n=l=1$ or n or l being greater than or equal to 2 and being distinguished in the electromagnetic field having n zero points in the azimuthal and m in a radial direction.

For micro-structures, a directly measurable quantity is the so-called filling fraction that is the volume of disposed features in a micro-structure relative to the total volume of a micro-

structure. For fibres that are invariant in the axial fibre direction, the filling fraction may be determined from direct inspection of the fibre cross-section.

In this application we distinguish between "refractive index", "geometrical index" and "effective index". The refractive index is the conventional refractive index of a homogeneous material – naturally, this is also used to describe the refractive indices of the various materials themselves in a microstructured medium". The geometrical index of a structure is the geometrically weighted refractive index of the structure. As an example, a microstructure consisting of 40% air (refractive index = 1.0) and 60% silica (refractive index $\approx$ 1.45) has a geometrical index of $0.4\times1.0 + 0.6\times1.45 = 1.27$. The procedure of determining the effective refractive index, which for short is referred to as the effective index, of a given micro-structure at a given wavelength is well-known to those skilled in the art (see e.g., Joannopoulos et al., "Photonic Crystals", Princeton University Press, 1995 or Broeng et al., Optical Fiber Technology, Vol. 5, pp.305-330, 1999).

Usually, a numerical method capable of solving Maxwell's equation on full vectorial form is required for accurate determination of the effective indices of micro-structures. The present invention makes use of employing such a method that has been well documented in the literature (see previous Joannopoulos-reference). In the long-wavelength regime, the effective index is roughly identical to the weighted average of the refractive indices of the constituents of the material, that is, the effective index is close to the geometrical index in this wavelength regime. Naturally, for a homogeneous medium, the effective refractive index is identical to the refractive index.

SUMMARY OF THE INVENTION

Looking at the general design approaches concerning dispersion compensating fibres operating in the fundamental mode, it is well established that large (negative) dispersion values – together with some degree of dispersion slope control - are obtained through rather complex index profile structures. Typically, these index profiles consist of a highly doped central core surrounded by an annular segment with depressed-index, which often is surrounded by an index ring (an annular segment of the fibre index profile with a refractive index value that is higher than the fibre cladding. The fundamental idea behind index profiles of this type is that in order to be

able to significantly modify the waveguide dispersion over a limited wavelength interval, it will be necessary for the (with wavelength) expanding mode field to experience a significant change in effective refractive index. In a more popular manner, it may be said that the mode field should "see" a strong shift in waveguiding structure as it expands out of the central core into the depressed annular segment and further into the raised annular segment.

It should be pointed out that although the major part of this patent application is dealing with aspects of index guiding PCFs, it is also addressing the possibility of designing and using HOM-DC-PCFs operating by the photonic bandgap effect. In this case it is noteworthy that PCFs operating by the PBG effect often are advantageous for providing large positive dispersion, and the ideas described in this patent application may enhance this performance. In connection with HOM-DC-PCFs of the PBG type it is highly relevant to note that such fibres may be designed to operate solely in the higher-order modes – allowing for complete fundamental mode suppression.

In a first aspect, the present invention relates to an optical fibre with a waveguide structure for supporting the transmission of light at a predetermined or operating wavelength λ_0, said optical fibre having a longitudinal direction and a cross-section perpendicular to said longitudinal direction, said optical fibre comprising:

- a central region having a centre axis in said longitudinal direction, said central region extending along and including said centre axis, said central region having an outer periphery with a maximum distance to the centre axis $r_{centre,\,max}$, a minimum refractive index $n_{centre,min}$, an effective refractive index $n_{centre,eff}$ and/or a resultant geometrical index $n_{g,centre}$,

- a core region extending along said longitudinal direction and surrounding said central region, said core region having an inner periphery that coincides with the outer periphery of the central region, an outer periphery with a maximum distance to the centre axis $r_{core,max}$, a maximum refractive index $n_{core,max}$, an effective refractive index $n_{core,eff}$ and/or a resultant geometrical index $n_{g,core}$,

- a cladding region extending along said longitudinal direction, said cladding region surrounding and neighbouring said core region, said cladding region having an inner periphery that coincides with the outer periphery of the core region, an outer periphery with a maximum distance to the centre axis $r_{cladding,max}$, a maximum refractive index $n_{clad,max}$, an effective refractive index $n_{clad,eff}$ and/or a resultant geometrical index $n_{g,clad}$.

Here, it is preferred that $n_{centre,eff}$ is equal to or lower than $n_{clad,eff}$ and $n_{clad,eff}$ is lower than $n_{core,eff}$ at the wavelength λ_o, and/or it is preferred that $n_{g,centre}$ is equal to or lower than $n_{g,clad}$ and $n_{g,clad}$ is lower than $n_{g,core}$ at the wavelength λ_o.

In the present context, the term 'region' is taken to mean a body constituting a part of the fibre that differs from other parts of the fibre in its material composition and/or refractive index and/or content of microstructural features.

In the present context, the geometrical (or average) index for a region with spatially varying refractive index (be it continuous or discontinuous (such as in the case of enclosed microstructures)), the geometrical index may be taken to mean the refractive index averaged over the volume or area in question (e.g. $(1/A)\int n(r,\varphi)drd\varphi$, over $r=r_{min}$ -> r_{max} and $\varphi=0$ -> 2π for a given region (e.g. central, core or cladding) represented in plane polar coordinates in a fibre cross section).

In a preferred embodiment, the fibre predominantly supports at least one higher order mode LP_{pq} at said predetermined wavelength λ_0. In the present context, the term 'predominantly supporting the transmission of light at a predetermined wavelength λ_0 in at least one higher order mode LP_{pq}' may be taken to mean that higher order modes account for more than 50% of the energy confined in the waveguide. Preferably higher order modes account for more than 80%, more preferred more than 90% and most preferred for more than 95% of the energy in the waveguide.

The outer periphery of the central region, the inner periphery of the core region and the outer periphery of the core region may be given by the functions $r_{centre}(\varphi)$, $r_{core,inner}(\varphi)$ and $r_{core,outer}(\varphi)$, respectively, representing the position vector of the corresponding peripheries described in a plane polar coordinate system with its centre

in the centre of the fibre (represented by the centre of the central segment) for a given fibre cross section.

It should be noted that the fibre according to the first aspect of the invention may be designed with a view to guiding higher order modes, and that the guidance of a particular mode may be favoured or disfavoured by, respectively, increasing or decreasing the refractive index at transversal locations of the waveguide, where the mode field is maximum. Thus the fundamental mode may be disfavoured by decreasing the refractive index at transversal locations, where the fundamental mode field is maximum (e.g. at the centre) and a particular higher order mode may be favoured by increasing the refractive index at transversal locations, where the mode field of the higher order mode in question is maximum. In short: A key design guide for improving a particular mode may be to locate index raised sections, where the mode intensity – and thereby the impact – of the mode in question is largest.

It is generally assumed that the basis material for the optical fibres according to the present invention is silica or silica doped with at least one member of the group consisting of Ge, Al, P, Sn, B, Er, Yb, Nd, La, Ho, Dy and/or Tm. However, the principles and ideas behind the invention are not limited to the use of these materials but may include other compound glasses (e.g., chalcogenide), polymers and low-melting point glasses.

The fibres according to the invention favouring higher order modes are advantageously used for dispersion compensation. Typically, higher order modes have lower cut-off wavelengths (i.e. the wave-length above which the waveguide in question cannot sustain the actual mode), the higher the mode (popularly the higher the indices n,l in $LP_{n,l}$). Further, for a given waveguide, the dispersion vs. wavelength for a given mode typically has large gradients around the cut-off wavelength of the mode in question. Thus for a given wavelength, the use of higher order modes for dispersion compensation thus has the advantage of favouring the use of larger waveguides, which in turn reduces the requirements to the fabrication of the fibres, eases handling (incl. splicing), and thus reduces overall costs.

Thus, it is within the present invention that $n_{clad,eff}$, $n_{core,eff}$, $r_{centre,max}$, $r_{core,max}$ and λ_o are adapted or selected so as to ensure that the fibre supports at least one higher order

mode. Alternatively or additionally, $n_{g,clad}$, $n_{g,core}$, $r_{centre,max}$, $r_{core,max}$ and λ_o are adapted or selected so as to ensure that the fibre supports at least one higher order mode.

It is within a preferred embodiment that $n_{clad,eff}$, $n_{core,eff}$, $r_{centre,max}$, $r_{core,max}$ and λ_o are adapted or selected such that V_{eq} defined as

$$V_{eq} = (2\pi/\lambda_o)(r_{core,max}^2 - r_{centre,max}^2)^{½}(n_{core,eff}^2 - n_{clad,eff}^2)^{½}$$

is larger than or equal to 1.2 or larger than or equal to 1.5, and $n_{centre,eff}$ is equal to or lower than $n_{clad,eff}$ in order for said optical fibre to guide light in a higher order mode at said predetermined wavelength, λ_o. Here, the values of $n_{clad,eff}$, $n_{core,eff}$, $r_{centre,max}$, $r_{core,max}$ and λ_o may be adapted or selected such that V_{eq} is larger than or equal to 1.8 or larger than or equal to 2.1. It is also within an embodiment that the values of $n_{clad,eff}$, $n_{core,eff}$, $r_{centre,max}$, $r_{core,max}$ and λ_o are adapted or selected such that V_{eq} is larger than or equal to 2.5.

Alternatively, $n_{g,core}$, $n_{g,clad}$, $r_{centre,max}$, $r_{core,max}$ and λ_o may be adapted or selected such that V_{eq} defined as

$$V_{eq} = (2\pi/\lambda_o)(r_{core,max}^2 - r_{centre,max}^2)^{½}(n_{g,core}^2 - n_{g,clad}^2)^{½}$$

is larger than or equal to 1.2 or larger than or equal to 1.5, and $n_{g,centre}$ is equal to or lower than $n_{g,clad}$ in order for said optical fibre to guide light in a higher order mode at said predetermined wavelength, λ_o. Also here, the values of $n_{clad,eff}$, $n_{core,eff}$, $r_{centre,max}$, $r_{core,max}$ and λ_o may be adapted or selected such that V_{eq} is larger than or equal to 1.8 or larger than or equal to 2.1. It is also within an embodiment that the values of $n_{clad,eff}$, $n_{core,eff}$, $r_{centre,max}$, $r_{core,max}$ and λ_o are adapted or selected such that V_{eq} is larger than or equal to 2.5.

In a preferred embodiment, the fibre has the same cross-section throughout its entire length. This need, however, not be the case. A variation of the cross-sectional dimensions of the features of the cladding and core regions in the longitudinal direction (be it periodic or non-periodic, continuous or discontinuous) is in principle possible.

In a preferred embodiment at least on of the peripheries of the central and the core region is substantially elliptical. This may be used to enhance the waveguiding properties of specifically oriented higher order modes. Here, both the central region and the core region may be substantially elliptical.

In another preferred embodiment at least one of the peripheries of the central and the core regions are substantially circular. Here, both the central region and the core region may be substantially circular.

In yet another preferred embodiment at least one or the peripheries of the central and the core regions are substantially rectangular. Here, the periphery of the core region may be substantially rectangular.

The terms ‚substantially elliptical' or ‚substantially circular' or 'substantially rectangular' are taken to mean that the deviation of the path in question from a true elliptical or circular or rectangular path, respectively, in a cross section of the fibre is less than 10% including process variations (cf. below).

Other peripheral forms than elliptical and rectangular are possible, e.g. substantially polygonal (e.g. triangular, specifically quadratic or hexagonal), possibly with curved edges, e.g. towards the centre.

In a preferred embodiment, the refractive index n_{centre} is independent of the azimuthal direction, $n_{centre} = n_{cente}(r)$ in a given cross section. In a further preferred embodiment, the refractive index n_{centre} is uniform ($n_{centre,0}$) within process variations in a given cross section.

The term 'uniform within process variations' is in the present context taken to mean uniform to within the limits that present day technology is capable of implementing for example silica doped refractive index profiles. Considering for example a down-doped silica region, such as using F-doping of silica, present doping methods, such as for example using chemical vapour deposition techniques, may yield a minor variation of the refractive index in radial direction. In the case of for example a void in the fibre centre, the process variation will naturally be significantly lower and in practice negligible.

In a preferred embodiment the core consists of a homogeneous 'background' material (i.e. without microstructural features) with refractive index $n_{core,back}$. In a further

preferred embodiment, the refractive index $n_{core,back}$ is independent of the azimuthal direction, $n_{core,back} = n_{core,back}(r)$ in a given cross section. In a further preferred embodiment, the refractive index $n_{core,back}$ is uniform ($n_{core,back,0}$) within process variations in a given cross section.

In a preferred embodiment the cladding region consists of a homogeneous 'background' material (i.e. without microstructural features) with refractive index $n_{cladding,back}$. In a further preferred embodiment, the refractive index $n_{cladding,back}$ is independent of the azimuthal direction, $n_{cladding,back} = n_{cladding,back}(r)$ in a given cross section. In a further preferred embodiment, the refractive index $n_{cladding,back}$ is uniform ($n_{cladding,back,0}$) within process variations in a given cross section.

In a special aspect of the present invention, said cladding region comprises an inner cladding region and an outer cladding region surrounding said inner cladding region. Here, the inner and outer cladding regions may have geometrical refractive indices in said cross-section of $n_{g,inner\ cladding}$ and $n_{g,outer\ cladding}$, respectively, where $n_{g,inner\ cladding} < n_{g,core}$, or the inner and outer cladding regions may have effective refractive indices in said cross-section of $n_{eff,inner\ cladding}$ and $n_{eff,outer\ cladding}$, respectively, where $n_{eff,inner\ cladding} < n_{eff,core}$.

In one or more preferred embodiments $n_{g,inner\ cladding} < n_{g,outer\ cladding}$ or $n_{eff,inner\ cladding} < n_{eff,outer\ cladding}$.

In a preferred embodiment the inner cladding region consists of a homogeneous 'background' material (i.e. without microstructural features) with refractive index $n_{inner\ cladding,back}$. In a further preferred embodiment, the refractive index $n_{inner\ cladding,back}$ is independent of the azimuthal direction, $n_{inner\ cladding,back} = n_{inner\ cladding,back}(r)$ in a given cross section. In a further preferred embodiment, the inner cladding background material has a refractive index $n_{inner\ cladding,back,0}$, which is uniform within process variations in a given cross section.

In a preferred embodiment the outer cladding region consists of a homogeneous 'background' material (i.e. without microstructural features) with refractive index $n_{outer\ cladding,back}$. In a further preferred embodiment, the refractive index $n_{outer\ cladding,back}$ is independent of the azimuthal direction, $n_{outer\ cladding,back} = n_{outer\ cladding,back}(r)$ in a given cross

section. In a further preferred embodiment, the outer cladding background material has a refractive index $n_{outer\ cladding,back,0}$, which is uniform within process variations in a given cross section.

In a special aspect of the present invention, an the central region of optical fibre is a void.

This has the advantage in connection with the present invention, that the fundamental mode of the waveguide is disfavoured (thus indirectly favouring higher order modes with enhanced dispersion compensating properties). Further, compared to prior art optical fibres the inclusion of a void as the central part of an optical fibre according to the present invention yields an improvements both in terms of lower bending losses as well as more abrupt cut-off properties of higher order modes, favouring dispersion compensating applications, where dispersion compensating fibres are coiled in small modules. The more abrupt cut-off properties are desired thereby allowing more negative dispersion to be achieved.

In a special embodiment, the central region comprises a fluid substance.

In the present context, the term 'fluid substance' is taken to mean a substance that at the normal operating temperatures and pressures of the invention act as a liquid or a gas, in other words is capable of flowing relatively easily (possibly using overpressure), for example a fluid substance with a non-linear optical response. The fluid may be added to the void after the production of the fibre. This has the obvious advantage of giving an enhanced design freedom as regards tailoring significant properties (including refractive index and attenuation) of the central region to a particular wavelength range.

In yet another preferred embodiment, the present invention relates to an optical fibre, wherein the central region is filled with a material from the group comprising, a gas, a liquid, a polymer, un-doped silica glass. Again, this further improves the possibilities of tailoring the refractive index and propagation loss of the central region of the core.

An advantage of designing fibres of un-doped silica is its simplicity and reproducibility.

In a preferred embodiment, the relative difference in geometrical refractive index or in effective refractive index between the core region and the cladding region is larger than 0,5 % and the difference between the average outer radial dimension of the core and central regions is larger than 2.3 times the predetermined wavelength λ_0.

In a preferred embodiment, the relative difference in geometrical refractive index or in effective refractive index between the core region and the cladding region is larger than 1 % and the difference between the average outer radial dimension of the core and central regions is larger than 1.7 times the predetermined wavelength λ_0.

In a preferred embodiment, the relative difference in geometrical refractive index or in effective refractive index between the core region and the cladding region is larger than 2 % and the difference between the average outer radial dimension of the core and central regions is larger than 1.2 times the predetermined wavelength λ_0.

In special versions of the above 3 embodiments aimed at providing multi-mode waveguides for dispersion compensating applications, the central region is a void and the surrounding core and cladding regions have substantially uniform refractive indices $n_{core} = n_{core,eff}$ and $n_{clad} = n_{clad,eff}$, respectively. The fibres may be made of silica based materials where n_{core} and n_{clad} are in the range from around 1.43 to 1.48.

According to a preferred embodiment, the predetermined wavelength or operating wavelength λ_0 is within the range from 1.3 μm to 1.7 μm. Here, the predetermined wavelength or operating wavelength λ_0 may preferably be within the range from 1.53 μm to 1.64 μm.

In a further embodiment or aspect of the present invention, said inner cladding region comprises a plurality of spaced apart cladding elements located in a background inner cladding material, each cladding element having a centre and extending in said longitudinal direction, and having a refractive index $n_{clad,elem}$ being lower than a refractive index $n_{inner\ cladding,back}$ of any background inner cladding material adjacent to the cladding elements in a given cross-section.

By 'the cladding element having a refractive index being lower than a refractive index of any background inner cladding material adjacent to the cladding elements in a given cross-section' may be understood that the refractive index $n(r,\varphi)$ described in a planar polar coordinate system with its centre in the centre of a cladding element fulfils the following relationship $n(r,\varphi) < n(r_c+\Delta r,\varphi)$, for $r < r_c$, $r_c(\varphi)$ describing the circumference of the cladding element in question and $\Delta r \to 0$.

The inclusion of microstructures (cladding elements) in the fibre cladding is advantageously used to enhance the waveguiding properties of the fibres by providing stronger refractive index contrasts. The use of microstructures further yields a higher flexibility in the choice of materials.

In a preferred embodiment, the cladding elements are of identical, essentially circular shape and placed in a predominantly periodic pattern (within a given region) when viewed in a cross section of the fibre. The cladding elements may, however, have other forms than circular, such as elliptical. Further, e.g. substantially polygonal (e.g. triangular, rectangular, specifically quadratic or hexagonal), possibly with curved edges, e.g. towards the centre are possible. Likewise, the cladding elements need not be of similar size, and may be positioned in a non-periodic pattern.

The term 'a predominantly periodic pattern' is in the present context taken to indicate that minor fluctuations of hole sizes and/or centre positions may be introduced during fabrication.

An advantage of the addition of microstructures (e.g. voids) in the fibre cross section is to further discriminate the relative guiding strength (and thereby e.g. the attenuation of the propagating mode). A further advantage hereof is to provide strongly enhanced spectral variations of the effective refractive indices of the higher-order modes in question, thereby significantly improving the design freedom using the number of microstructures, their relative sizes, mutual positions and refractive indices as design parameters. Therefore, by using microstructured sections of the fibre cladding and at the same time controlling the dimensions of a central region, strongly improved higher-order mode dispersion values may be obtained.

Further, the strong dispersion compensating properties of higher-order modes are enhanced using the ability to spectrally shape the refractive index of photonic crystal or microstructured sections of optical fibres. Furthermore, central parts of the photonic crystal fibre are designed to enhance the mode propagation properties of higher-order modes while at the same time decreasing the mode guidance of the fundamental optical mode (the central void providing low guidance of the fundamental mode), and furthermore allowing enhanced mode field distribution control (e.g., for lowering the influence of undesired non-linear processes in the dispersion compensating fibre).

The key advantage of optical fibres according to the invention is that the microstructured part of the fibre provides a significant – and generally much stronger – index suppression than obtainable with standard fibre doping techniques, hereby allowing the tailoring of the effective index variation experienced by the higher-order mode as a function of wavelength λ. In contrast to standard HOM-DCFs, the microstructured part of the fibre will further allow a significantly improved tailorability of the spectral dependency of the involved refractive index, n. Key design parameters for tailoring $n(\lambda)$ are the number of voids and their relative size and location, and they may according to the present invention be varied as described later.

In a preferred embodiment, said cladding elements are arranged in a pattern, which ensures an at-most-two-fold rotational symmetry about said centre axis.

Such fibres may be especially relevant for enhanced propagation of higher-order modes of the LP_{11} type because the restricted rotational symmetry of the refractive indices and the mutual relative size of the various regions of the fibres fits the modal shape of the electromagnetic field of this mode.

In a preferred embodiment, the core region is rectangular and the cladding elements or the inner cladding region are arranged so that the core and cladding regions together show a two-fold rotational symmetry about the centre axis of the optical fibre.

In a preferred embodiment, the cladding elements included in the inner cladding region are located in at least one layer around said core region.

The background for designing fibres according to this preferred embodiment of the invention is that the arrangement of cladding elements in rings around the core region with common centres lowers the risk of asymmetries inducing undesired polarisation mode dispersion. For this reason rings with a larger number (i.e., more than 6) of cladding elements are expected to provide improved circularity of the mode-field distribution in order to decrease undesired effects such as polarization mode dispersion (PMD) or to provide increased mode-matching to standard fibres, e.g. for reducing splicing losses.

In a preferred embodiment the cladding elements are located in one relatively thin layer around the core region. By the term 'the cladding elements are located in one layer' is in the present context understood that the cladding elements are arranged in an annular ring whose radial thickness is essentially determined by the maximum radial dimension of the cladding elements constituting the ring.

In a preferred embodiment, the cladding elements are arranged in a number of concentric layers, preferably at least 3, each layer preferably comprising a minimum number of elements, the innermost layer preferably comprising a minimum of 5, the middle layer a minimum of 10, and the outermost layer a minimum of 15 cladding elements.

In a preferred embodiment, the cladding elements are effective to provide index guiding of higher-order modes guided by the waveguide structure, and the core and inner cladding regions are mutually adapted so that the at least one higher order mode guided by the fibre exhibit negative dispersion.

In another preferred embodiment, the fundamental and at least one higher-order mode are guided, and in which the radial dimensions and the refractive indices of the central, core, inner cladding and outer cladding regions are selected to provide a higher order dispersion less than about −200 ps/km/nm at a specified wavelength, the specified wavelength being located in the wavelength range from 1500 nm to 1650 nm, such as in the wavelength range from 1520 nm to 1610 nm, such as in the

wavelength range from 1530 nm to 1570 nm, such as being at a wavelength of about 1550 nm.

In a preferred embodiment, the optical fibre is designed to have a dispersion for the higher order LP11 mode of less than −200 ps/km/nm, preferably less than −500 ps/km/nm, such as less than −1000 ps/km/nm.

In a preferred embodiment, said multitude of spaced apart cladding elements of the inner cladding region comprises cladding elements with at least two different cross-sectional areas, and wherein cladding elements of predominately equal cross-sectional areas are arranged within prescribed minimum and maximum distances from the centre of the fibre.

The advantage thereof is that such fibres enhance the ability to modify the effective refractive index of the mode as a function of wavelength in a prescribed manner. It, therefore, enhance the design flexibility and possible performance of the fibres.

One preferred embodiment displays two separate adjacent annular rings in the inner cladding region (viewed in one cross-section of the fibre), each containing identical cladding elements with identical cross-sections, the cladding elements of the two rings having different cross-sectional areas.

In another preferred embodiment the inner cladding region comprises one annular ring circumfering the core containing cladding elements with two different cross-sectional areas in alternating order (in an azimuthal direction).

In a preferred embodiment, said multitude of spaced apart cladding elements are of equal cross sectional form and area, each having a centre and an average radial dimension $r_{clad,elem}$, and positioned in the inner cladding region with equal centre to centre spacing Λ. In a further preferred embodiment, the fibres comprise silica glass and/or polymer material (having refractive indices in the range 1.42-1.50 and 1.30-1.90, respectively). It is further preferred that the central region and the cladding elements are voids. Further, it is advantageous with respect to the dispersion compensating

properties that central void has a larger average radial dimension than the cladding elements.

In a preferred embodiment, said multitude of spaced apart cladding elements comprises voids.

In a preferred embodiment, said multitude of spaced apart cladding elements comprises a fluid substance.

In a preferred embodiment, the refractive indices of the core $n_{core,back,0}$, the inner cladding background $n_{inner\ cladding,back,0}$ and outer cladding $n_{outer\ cladding,back,0}$ are uniform and equal within process variations in a given cross section.

In a preferred embodiment, the core and cladding material is undoped silica. This has the advantage of simplicity by avoiding processing steps involving doping, the necessary differences in refractive indices being solely created by the central region and the cladding elements (preferably voids).

In a preferred embodiment, the inner cladding region comprises one or more annular segments having a higher geometrical refractive index $n_{g,ann\text{-}seg}$ or a higher effective refractive index $n_{eff,ann\text{-}seg}$ than the refractive index of any inner cladding background material adjacent to it.

In the present context, the term annular segment is taken to mean a body that, when viewed in a cross-section of the fibre, circumferes the centre of the fibre. The annular segment may have a circular, elliptical or any other closed-ring geometry.

This has the advantage of providing an extra tool for tailoring the index profile of the cladding region. Fibres according to the present invention having a central void and a raised index annular segment surrounding the void have the advantage of providing improved splicing performance, when spliced to standard optical fibres using fusion splicing. One of the problems involved in the splicing of microstructured fibres of pure silica is that the voids may collapse as the PCF is heated. In a fibre according to the present invention, the central void may collapse, but due to the raised index in the

annular section of the fibre the heated section may still maintain an index-guiding core.

In yet another preferred embodiment, the present invention relates to optical fibres, where the design parameters have been selected to obtain strong dispersion compensation ability. Analysis of fibre designs according to the present invention has shown that it is advantageous to chose fibres, wherein the average radial dimension of the central region is chosen to be between 0.1 μm and 2.0 μm, and the average outer radial dimension of the core is chosen to be between 2.0 μm and 5.0 μm, and wherein a plurality or all of the cladding elements of the inner cladding region are located within a distance of 10 μm from the centre of the fibre.

The average radial dimension of the central region of the core equals its radius if the core is perfectly circular in cross section of the fibre and represents a mean value if its cross-sectional shape deviates therefrom (e.g. due to intended or unintended irregularities or elliptical or polygonal shapes). The same holds for the average outer radial dimension of the core, only that it also represents a mean of the 'outer' boundary of the annular region.

In a preferred embodiment, the higher geometrical refractive index $n_{g,ann-seg}$ of the annular segment is achieved by doping. Dopants are preferably selected among the group comprising Ge, F, P, Sn, Bm, Er, Yb, Nd, La, Ho, Dy, Tm and other rare-earth and transition metal ions.

In a preferred embodiment, the core or cladding regions comprise silica glass.

In a preferred embodiment, the core or cladding regions comprise a polymeric material.

In a preferred embodiment, all of or parts of the core or cladding regions are doped with one or more dopants from the group comprising Ge, F, P, Sn, Bm, Er, Yb, Nd, La, Ho, Dy, Tm and other rare-earth and transition metal ions,

In a preferred embodiment, said core region comprises one or more core elements located in a background core material and extending along said longitudinal direction,

each of said one or more core elements having a centre and a refractive index $n_{core,elem}$ being higher than a refractive index of any background core material $n_{core,back}$ adjacent to the core element in a given cross-section.

Such configurations may be used to impose an arbitrary degree of symmetry on the core part of the fibre (which may or may not be reflected in the cladding part of the fibre) aiming at enhancing certain modes and suppressing other modes.

The high-index core elements may be created my building a preform containing a central glass tube with the glass stabs corresponding to the high-index core elements positioned at equivalent positions in the core, and surrounded by 'background core' glass stabs of a smaller diameter than the high-index stabs, so that they collapse to homogeneous background glass matrix around the high-index regions. The refractive index of the 'high-index'-stabs may alternatively or supplementary be modified by UV-treatment.

In a preferred embodiment, two core elements having a higher refractive index than the background core material are located opposite each other on an axis through the centre of the fibre when viewed in a cross-section of the fibre. Such a configuration showing a twofold rotational symmetry about the fibre longitudinal axis favours the propagation of a two-lobed higher order mode, such as the 2. order mode LP_{02}. It is preferred that the distance between the centre of the fibre and the centre of one of the core elements is in the range from 3.0 μm to 20.0 μm.

In a preferred embodiment the core elements each consist of a homogeneous 'background' material with refractive index $n_{core,elem}$. In a further preferred embodiment, the refractive index $n_{core,elem}$ is independent of the azimuthal direction, $n_{core,elem} = n_{core,elem}(r)$ in a given cross section when viewed in a planar polar coordinate system with its centre coinciding with the centre of the core element. In a further preferred embodiment, the refractive index $n_{core,elem}$ is uniform ($n_{core,elem,0}$) within process variations in a given cross section.

In a preferred embodiment, said one or more core elements are fully enclosed by said background core material and individually spaced apart.

In a preferred embodiment, said one or more core elements are arranged in a pattern, which ensures an at-most-two-fold rotational symmetry about said centre axis.

Such fibres may be especially relevant for enhanced propagation of higher-order modes of the LP_{11} type because the restricted rotational symmetry of the refractive indices and the mutual relative size of the various regions of the fibres fits the modal shape of the electromagnetic field of this mode.

In a preferred embodiment, said central region comprises undoped silica.

In a preferred embodiment, said central region comprises a polymeric material.

A further aspect of the invention concerns a dispersion compensating module comprising an input section, a length of fibre according previous aspects of the present invention, and an output section, said input section and said output section each containing a Bragg-grating structure, said input section being designed to perform mode conversion between a fundamental mode and a higher-order mode, and said output section being designed to perform mode conversion between said higher-order mode and said fundamental mode, and said length of fibre has a negative dispersion for said higher-order mode.

In a preferred embodiment, the Bragg-grating structures are provided by illumination with an interference pattern of ultra-violet light.

In a further preferred embodiment the negative dispersion of the length of fibre of the dispersion compensating module is more negative than −200 ps/nm/km, more preferred more negative than −500 ps/nm/km, etc.

In yet another preferred embodiment, the present invention relates to an optical fibre communications system comprising an optical fibre transmission path, a source of radiation of wavelength λ_s, and detector means for detecting radiation of wavelength λ_s, said detector means being separated from said source of radiation by said optical fibre transmission path connecting said source and said detector means, said optical

fibre transmission path comprising input mode conversion means for mode conversion between fundamental and higher-order modes, a length L_{DCF} of an optical fibre according to previous aspects of the invention having dispersion $D_{DCF}(\lambda_s)$ at λ_s, in which fibre the optical radiation is predominately propagating in a higher-order mode, output mode conversion means for mode conversion between higher order modes and fundamental modes, and a length L_{SM} of single mode optical fibre having chromatic dispersion $D_{SM}(\lambda_s)$ at λ_s, in which fibre the optical radiation is propagating in the fundamental mode, with L_{DCF} and L_{SM} selected such that $L_{DCF} \cdot D_{DCF}(\lambda_s) + L_{SM} \cdot D_{SM}(\lambda_s)$ is approximately equal to zero.

In the present context 'cromatic dispersion' is taken to mean the sum of 'waveguide dispersion' and 'material dispersion'.

The term 'approximately equal to zero' is in the present context taken to mean that $[L_{DCF} \cdot D_{DCF}(\lambda_s) + L_{SM} \cdot D_{SM}(\lambda_s)]/[L_{SM} \cdot D_{SM}(\lambda_s)]$ is numerically less than 5%, preferably less than 1%.

In a preferred embodiment $L_{DCF} \cdot D_{DCF}(\lambda_s) + L_{SM} \cdot D_{SM}(\lambda_s)$ is numerically less than 50 ps/nm, more preferred less than 10 ps/nm, most preferred less than 1 ps/nm.

A further aspect of the invention concerns a preform for producing fibres according to previous aspects of the present invention, wherein an elongated cylindrical capillary centre tube being defining a centre axis and being made of a material with refractive index n_{cntt}, is stacked together with a multitude of N individual elongated cylindrical surrounding bodies being made of a material with refractive indices $n_{sb,i}$, $i = 1,2, \ldots, N$, said centre tube is centrally located among said surrounding bodies, and at least one circumfering tube being made of a material with refractive index $n_{circt,j}$ surrounding said centre tube and said surrounding bodies, said centre tube, said surrounding bodies and said circumfering tube are of substantially equal length,

In a preferred embodiment, the elongated cylindrical tubes and bodies have a circular cross section perpendicular to their longitudinal axis. They may, however, have other cross sectional forms than circular, such as elliptical or polygonal.

In a preferred embodiment, said surrounding bodies are identical capillary tubes being made of a material with refractive index n_{sb}, and the refractive index n_{cntt} of said centre tube is larger than the refractive index n_{sb} of said surrounding capillary tubes.

In a preferred embodiment, said surrounding bodies comprise a mixture of one or more first identical rods being made of a material with refractive index $n_{sb,rod-1}$ and one or more second identical rods being made of a material with refractive index $n_{sb,rod-2}$ and one or more identical capillary tubes being made of a material with refractive index $n_{sb,cap-1}$.

In a preferred embodiment, said one or more first identical rods consist of 2 rods placed adjacent to and on opposite sides of said centre tube, and the preform has an at-most-two-fold rotational symmetry about said centre axis.

In a preferred embodiment, said surrounding bodies comprise a mixture of one or more first identical rods being made of a material with refractive index $n_{sb,rod-1}$ and one or more identical capillary tubes being made of a material with refractive index $n_{sb,cap-1}$.

In a preferred embodiment, said one or more identical capillary tubes consist of 2 tubes placed adjacent to and on opposite sides of said centre tube, and the preform has an at-most-two-fold rotational symmetry about said centre axis.

It is to be understood that both the foregoing general description as well as the following detailed description are merely exemplary of the invention, and are intended to provide an overview or framework for understanding the nature and character of the invention as it is claimed. The accompanying drawings are included to provide a further understanding of the invention, and are incorporated in and constitute a part of this specification. The drawings illustrate various embodiments of the invention, and together with the description serve to explain the principles and operation of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows schematically the refractive index profile of a prior-art triple-cladding dispersion compensating fibre.

FIG. 2 illustrates schematically the refractive index profile of a prior-art higher-order mode dispersion compensating fibre.

FIG.3 shows schematically the refractive index profile of a prior-art, single-mode optical fibre having a central void surrounded by a raised index ring and an outer cladding.

FIG.4 schematically illustrates an example of the cross section of a fibre according to the present invention comprising a central void surrounded by a high-index region, which acts as a core for higher-order modes, and two lower index regions acting as an inner and an outer cladding region, where the inner cladding region may have a similar or lower refractive index compared to the outer cladding. Some or all regions surrounding the central void are solid.

FIG.5 illustrates the refractive index profile and the radial mode distribution of the LP_{11} higher-order mode in a fibre according to the present invention.

FIG.6 shows the spectral dispersion variation for the fundamental and higher-order modes of a fibre according to the present invention. The dispersion results are calculated using a full-vectorial mode solver (the specific implementation is generally known as a plane-wave method).

FIG.7 illustrates corresponding values of dispersion (in ps/km/nm) and dispersion slope (in ps/km/nm^2) calculated (by a scalar approximation) for the LP_{11} mode in various implementations of HOM-DC-PCF fibres according to the present invention. The fibre designs all have a central void surrounded by a raised index placed in an annular distribution around this void and further surrounded by a microstructured section forming a strongly depressed equivalent refractive index ring.

FIG.8 shows a schematic example of the cross section of a fibre according to the present invention that utilises a central void surrounded by a raised index ring and a

microstructured cladding section. a) The microstructured cladding section is formed by voids predominantly placed in a constant distance from the fibre centre. b) More than one annular ring of voids are placed to form the inner microstructured cladding.

FIG.9 schematically illustrates an example of the cross section of a fibre according to the present invention comprising a central void, and a high-index region surrounding the cenral void. The cladding comprises a microstructure with a large number of low-index features. The central void has a larger size than the central void. The fibre may guide light in a higher order mode through the mechanism of total internal reflection.

FIG.10 illustrates the mode indices of the fundamental and two higher order modes for a fibre with a design as schematically shown in Fig.9. The figure further illustrates the effective indices of two full-periodic structures corresponding to the cladding and the core structures.

FIG.11 schematically illustrates a) an example of a fibre according to the present invention in which a central void is placed in a homogeneous material (typically pure silica) forming the index guiding core region, and in which the outer cladding is formed by a microstructured cladding, where voids voids are placed in a close-packed arrangement – and b) an example of the cross section of a fibre according to the present invention that utilises a central void surrounded by an un-doped and homogeneous index section, and further surrounded by different sections of microstructured cladding – in the specific case the void dimensions are different for the illustrated cladding sections.

FIG.12 schematically shows an example of the cross section of a fibre according to the present invention that utilises a central void surrounded by annular rings of doped (index raised or index lowered) material and also including annular sections of microstructured cladding.

FIG.13 schematically illustrates an example of the cross section of a fibre according to the present invention comprising a central void surrounded by a high-index region, which acts as a core for higher-order modes, and two lower index regions acting as an inner and an outer cladding region, where the inner cladding region may have a similar

or lower refractive index compared to the outer cladding. In this case, the two cladding regions are homogeneous, whereas the core region comprises core features having a higher refractive index than the core background material. The position of the high-index core features may be chosen to favour specific higher order modes, for example such that the high-index core features are positioned at spatial positions where specific higher order modes have their maximum.

FIG.14 shows schematically a fibre according the present invention that resembles the fibre in Fig. 13, but where the low-index inner cladding region is realized using micro-structuring.

FIG.15 schematically shows an example of the cross section of a fibre according to the present invention comprising a central void surrounded by a doped and microstructured core, which furthermore is made non-circular symmetrical by varying the local pitch and hole size of the microstructuring. The holes may be placed within the up-doped region or outside.

FIG.16 schematically shows an example of the cross section of a fibre according to the present invention comprising a central void surrounded by an non-circular core region and a microstructured inner cladding, where the inner cladding features are placed in a non-circular symmetric manner with respect to the centre of the fibre.

FIG.17 schematically illustrates an example of the cross section of a fibre according to the present invention comprising an elliptically shaped central void around which a raised annular core section (in this specific case also of elliptical outer shape) is used to enhance higher-order mode propagation properties.

FIG.18 illustrates how a fibre according to the present invention also is used for mode conversion at the input and output ends of the dispersion compensating fibre through the application of fibre Bragg gratings written by ultra-violet light in the doped sections of the core.

FIG.19 schematically shows a splicing section, in which a fibre according to the present invention is spliced together with a standard optical fibre, e.g., the transmission fibre.

FIG.20 schematically shows a preform for fabrication of a fibre according to the present invention. The preform comprises a central high-index capillary tube that is surrounded by a number of lower index capillary tubes. The capillary tubes are placed in a large overcladding tube.

FIG.21 schematically shows another preform for fabrication of a fibre according to the present invention.

FIG.22 schematically shows another preform for fabrication of a fibre according to the present invention.

DETAILED DESCRIPTION OF THE INVENTION

If we take point of reference in the well known dispersion compensating fibre (DCF) technique, it should be noted that the first DCF designs were step index fibres, where the zero dispersion wavelength was moved to wavelengths above 1550 nm by increasing the core index and narrowing the core diameter (see e.g., Onishi, Koyano, Shigematsu, Kanamori and Nishimura, IEE Electronics Letters, Vol.30, No.2, 1994; and Bjarklev, Rasmussen, Lumholt Rottwitt and Helmer, Optics Letters, Vol.19, No.7, pp.62-64, 1994). Later more advanced double and triple cladding designs were utilised (see e.g., Antos, and Smith, IEEE Journal of Lightwave Technology; vol.12, No.10, pp.1739-1745, 1994; Vengsarkar, Miller, Haner, Gnauck, Reed and Walker, OFC'94, paper ThK2, pp.222-227, 1994; Onishi, Fukada, Kanamori and Nishimura, ECOC'94, pp.681-684,1994; and Akasaka, Sugizaki, Umeda and Kamiya, OFC'96, paper ThA3, pp.201-202,1996). These designs have several advantages over the step index design – among others is negative dispersion slope to provide partly or full dispersion slope compensation. Slope compensation plays an important role for broad band transmission (WDM systems) where dispersion typically must be compensated over 30nm or broader at wavelengths around 1550nm. Conventional dispersion compensating fibres are often not capable of providing dispersion compensation over

such broad wavelength ranges (for example for transmission over long lengths of CORNING LEAF® fibre. Fibres according to the present invention may be used either solely as dispersion compensating fibres or as dispersion slope compensating fibres in combination with conventional dispersion compensating fibres.

In Fig. 1 a prior-art DCF triple-cladding fibre design is illustrated. A DCF of this type has a narrow highly-doped core (10) (typically germanium is used as index raising dopant) surrounded by a depressed cladding (11) (typically fluor-doped to refractive index levels in the order of −0.5 % compared to the refractive index of undoped silica (around 1.444 at 1.55μm) This germanium doping in the central part of the fibre may typically result in a raising of the refractive index of 2-3 % using rather narrow core radii in the order of 1-2 μm. The highly doped core is favourable as it enables a high negative dispersion, but the drawback is increased attenuation (as described by Grüner-Nielsen et al., ECOC´2000 pp.91-94). The depressed cladding decreases the dispersion and is necessary to obtain negative dispersion slope around 1550 nm. Another index ring (12) with raised index compared to the cladding is often introduced to improve bending properties, but the refractive index is normally not raised much above 0.5 %, since a high index value will lead to multimode operation of the fibre. Outermost the fibre has a pure silica cladding (13).

By further examining the index profiles (and ideas behind these) for higher-order mode dispersion compensation in standard optical fibres the research points towards refractive index profiles of a type as schematically shown in Fig.2. In these types of fibre, we again find the relatively strongly doped central core (20), but this time surrounded by an inner cladding ring (21), which is often un-doped. An annular ring of raised refractive index (22) ensures that the higher order modes (and here it should be noted that the LP_{02} mode often is very well guided and has a higher cut-off wavelength than the LP_{11} mode) are allowed to spatially switch between predominant location within the central core to stronger location to the raised index ring (22) as the wavelength is increased. It is this spatial power redistribution, and the related change in effective refractive index of the mode that enables the large negative dispersion values. Finally, also this kind of HOM-DCF has an outer cladding (23) – typically made of pure silica.

It should be noted that we throughout this description generally will assume that the basis material is silica or doped silica, since this is the most commonly used material for fabrication of optical fibres. However, the principles and ideas behind the invention is not limited to these material combination, and it may for future applications, where new spectral ranges of the optical fibre technology is explored, be more advantageous to use different material compositions, such as (but not limited to) different compound glasses (e.g., chalcogenide), polymers and low-melting point glasses.

It is at this point obvious that strong dispersion compensation generally is obtained by spectrally shifting the effective refractive index of the guided mode(s). This requires refractive index profile control on a sub-wavelength scale, and the effect is closely related to the spatial redistribution of the optical mode as a function of wavelength. It should, however, also be stressed that a preferred approach – especially when it comes to higher-order mode dispersion compensation – is to adapt the effective index profile to the specific mode that we want to use in the dispersion compensating process. If we using this selective approach at the same time may disfavour some of the undesired modes, a better signal-to-noise ratio of the compensated system may be obtained. The reason for this is that in a HOM-DCF compensator, the performance is limited by the ability to fully convert the LP_{01} mode from the transmission fibre to the desired higher-order mode. Whenever this mode conversion is not completely effective, some part of the optical power is carried through the HOM-DCF in a "wrong" mode that consequently is not dispersion compensated. One could argue that this would not be harmful, provided that the "wrong" modes are not converted into the fundamental mode in the transmission fibre that often is placed at the output end of the HOM-DCF. However, since we may neither be sure that the output mode converter is completely perfect, a fraction of the "wrongly" dispersion modified modes may leak through to the detector –resulting in increased system noise. For this reason it is advantageous if we may design the fibre in a manner that discriminate the undesired modes to the highest possible degree.

To understand how this may be accomplished, we may take point of reference in the mode properties of the single-void fibre design disclosed in patent application WO 00/55661. The refractive index profile of the step-index single-void fibre is schematically illustrated in Fig.3. In this illustration, the centrally placed void (30) is surrounded by a raised refractive

index ring (31) forming the fibre core. Outermost we find the homogeneous cladding (32). The core (31) has a refractive index n_{core} and the cladding (32) has a refractive index n_{clad}. As previously described this fibre design was developed in order to be able to enhance the fundamental mode spotsize compared to solid core optical fibres, and hereby increase the threshold optical powers for non-linear processes in the optical fibres.

The enlargement of the mode area – or spotsize – of the single-void designs is, however, at the cost of having mode field distributions that are strongly non-gaussian, and as a matter of fact the fundamental mode field will typically have a remarkable dip in the mode field strength in the central part of the fibre. The present inventors have realised that this also may be interpreted as a weakening of the guiding strength of the fundamental mode in the optical fibre compared to solid core designs. Using a somewhat simplified formulation (with relevance to index guiding fibres) we may say as follows: A modification of an optical waveguide by respectively increasing or decreasing the refractive index value at transversal locations, where the mode field is maximum, is a method of improving or disfavouring the mode guiding properties compared to the original waveguide. Using this viewpoint, the present inventors have realised that - properly designed - the single-void design is favourable for guiding of the LP_{11} mode, which has a very small mode field intensity in the central part of the optical fibre.

For a standard, step-index fibre, the cut-off wavelength may be determined using the V-parameter given by:

$$V = kr(n_{core}^2 - n_{clad}^2)^{½},$$

where k is the free-space wave number equal to $2\pi/\lambda$ (λ is the free-space optical wavelength), r is the core radius and n_{core} and n_{clad} is the core and cladding refractive index, respectively. The fibre is single mode for V smaller than a given cut-off value, $V_{cut\text{-}off}$, of approximately 2.14.

For the fibres disclosed in WO 00/55661 and schematically shown in Fig. 3, an equivalent V-parameter may as a first approximation be written as:

$$V_{eq} = k(r^2 - r'^2)^{½}(n_{core}^2 - n_{clad}^2)^{½},$$

where k is the free-space wave number equal to $2\pi/\lambda$ (λ is the free-space optical wavelength), r is the core radius (half the distance (34)) and r′ is the radius of the central void (half the distance (33)), and n_{core} and n_{clad} is the core and cladding refractive index, respectively. This approach, however, may predict a different cut-off value, $V_{eq,cut\text{-}off}$, than

for the step-index fibre. The reason for this is in V_{eq}, the refractive index between the centre region and the core region is not taken into account. Typically, n_{centre} is lower than n_{clad} and $V_{eq,cut\text{-}off}$ may be lower than 2.14 – as shall be discussed at a later stage.

As a first approximation, for the fibre in Fig. 3 to be single-mode V_{eq} must be smaller than approximately 2.14. This is a conservative value, as the fibre may be multi-mode at a lower Veq value – as discussed above. Hence, we find multi-mode behaviour for $(r^2-r'^2)^{½}$ larger than $2.14/k\ (n_{core}^2-n_{clad}^2)^{-½}$. The correct value is expected to be for a lower factor than 2.14, wherefore, we may find multi-mode behaviour for $(r^2-r'^2)^{½}$ larger than $x/k\ (n_{core}^2-n_{clad}^2)^{-½}$, where x is somewhat lower than 2.14. Since the fibres disclosed in WO 00/55661 are made form silica-based materials, n_{core} and n_{clad} are typically in the range from around 1.43 to 1.48. As an example, an index difference of around 1% between the core and cladding index (for example n_{clad}=1.444 and n_{core}=1.458) gives a maximum value of $(r^2-r'^2)^{½}$ for single-mode operation at 1.55μm of around 2.6μm. Hence, for index differences between core and cladding *larger* than 1%, $(r^2-r'^2)^{½}$ larger than 2.6μm will provide a multi-mode fibre. Again, this may be a conservative prediction, and the fibre may operate in a multi-mode also for somewhat smaller dimensions of the core. For index difference around 0.5%, the corresponding $(r^2-r'^2)^{½}$ value for multi-mode behaviour is around 3.5μm for λ=1.55μm, and for index-differences around 2%, the minimum $(r^2-r'^2)^{½}$ value for multi-mode behaviour is around 1.8μm for λ=1.55μm. Referring to Fig. 3, this means that a fibre with a design as schematically shown in Fig. 3 that is operating at a wavelength λ and has an index difference of more than 1% between the core (31) and cladding (32), will be multi-mode $(r^2-r'^2)^{½}$ larger than at least 1.7 times λ.

The present invention covers such multi-mode optical fibres that are used for dispersion compensating applications. Typically, such fibres will be operated at a V_{eq} value close to the cut-off of a higher-order mode.

The present invention also covers a number of improved designs of multi-mode fibres. An example of a multi-mode fibre for dispersion compensating applications is schematically indicated in Fig. 4. The fibre has a central void (41) surrounded by a core region (43) comprising a material of refractive index n_{core}. In the fibre shown in Fig. 4, the core region (43) is homogeneous, hence the background refractive index of the core, $n_{core,back}$ and the effective refractive index of the core, $n_{core,eff}$, is identical to n_{core}. The cladding of the fibre is divided into (at least) two regions, an inner cladding (45) comprising a material of refractive

index $n_{clad,inner}$ and an outer cladding (46) comprising a material of refractive index $n_{clad,outer}$. The inner cladding (45) has $n_{clad,inner}$ that is lower than n_{core}. The fibre is further characterized by a maximum void dimension (40), a maximum core dimension (42) and a maximum inner cladding dimension (44). In preferred embodiments, $n_{clad,inner}$ is lower than $n_{clad,outer}$. In comparison with the fibre in Fig.3, this may provide improvements both in terms of lower bending losses as well as more abrupt cut-off properties of higher order modes. Both improvements are of high importance for dispersion compensating applications, where dispersion compensating fibres are packed in small modules by coiling the fibre. The more abrupt cut-off properties are desired as these provide stronger dispersion in the fibres (i.e. more negative dispersion may be achieved).

Fig.5 shows an example of the radial distribution of a higher-order mode in a fibre with a design as schematically shown in Fig. 4. The radial mode distributions have for simplicity been calculated using a scalar mode solver, and the depicted electrical field strengths are, therefore, corresponding to the LP_{11}-modes (linearly polarised modes) in the structure. Fig.5 further shows the equivalent refractive index distribution used as input for the calculations. It should be noted that the refractive index profile shows the central void (with refractive index of 1.0 – corresponding to air or vacuum), a raised index section surrounding this central void. The mode field is shown (also at the wavelength of 1550 nm) for the LP_{11} mode in the azimuthally direction, where it is maximum, and we note that the maximum value has been normalised to 1.0 for convenience of the illustration. We note that the higher order mode field has minimum field intensity in the central area of the fibre, where the central void is located. The negative influence on the LP_{11} mode due to the lack of high-index material in the central part of the fibre will, therefore, only be very limited, whereas the fundamental mode (also guided by the fibre structure) will have a strongly modified mode field in the central part of the fibre compared to a standard step-index fibre. This modification, which may be seen as a pronounced intensity dip in the centre will not only result in weaker guidance of the LP_{11} mode, but we may even expect that the LP_{01} mode could be attenuated strongly compared to the LP_{11} mode – either due to a gas or other attenuating material placed in the central void, or by inducing micro-deformation losses in the fibre. The fibre designs according to the invention, therefore, allow for useful and controllable mode discrimination. Insertion of a gas or for example polymer materials into the central void may also be used for dynamic dispersion control. This may be

achieved by having an external source influencing the properties of the material inserted into the central void. This influence may for example by obtained using temperature, pressure, non-linear optical or acousto-optical effects.

In the examination of the fibre designs according to the invention, the inventors have been applying several numerical tools, including more rapid analysis through scalar modelling of circular symmetric equivalent refractive index profiles through accurate vectorial analysis of corresponding structures. The methods employed are described in several publications, including Broeng et al., Optical Fiber Technology, Vol. 5, pp.305-330, 1999. To illustrate examples of the dispersion compensating capability of the fibres according to the invention, and to further show the clear differences between the propagation properties of different modes in the fibres, Fig.6 shows results from calculations on a fibre with a design as schematically shown in Fig. 4 that were obtained using a so-called plane-wave, vectorial model. In the specific example, the fibre is characterized by a central void with a radius of 0.4 μm (a maximum diameter of 0.8μm of the central void). Surrounding the central void is a solid core region comprising material with a refractive index of 1.480 and a maximum outer dimension of the core region of 2.2 μm. The inner cladding of the fibre has a refractive index of 1.446 and a maximum dimension of 4.2 μm. The outer cladding region comprises material with a refractive index of 1.450 and the outer cladding has a maximum dimension around 125μm.

Fig.6 illustrates (for reference) the material dispersion of silica glass as a function of wavelength. The dispersion shown for 1.order modes (equivalent to LP_{01} modes in standard optical fibres) shows relatively slow variation with wavelength, whereas the 2.order mode dispersion (equivalent to LP_{11} modes in standard optical fibres) demonstrates pronounced negative dispersion values around the wavelength of 1550 nm. It should be noted that the exact dispersion minimum only should be taken as an indication of the strong dispersion compensating capabilities of the fibres according to the invention, and very time consuming analysis with high accuracy should be used to determine the precise value. The minimum in the dispersion curve of the second-order mode occurs at wavelengths close to the cut-off of second order mode.

It is here worth noticing that the approximate expression of the cut-off properties of fibres with a central void, which has been discussed previously, predicts a V_{eq} value of 1.3 around the cut-off wavelength of approximately 1.55μm.
This V_{eq} value is seen to be (significantly) lower than 2.14 and is attributed to the fact that n_{centre} is (significantly) lower than n_{clad}. For the calculation of V_{eq}, the following parameters were used: $\lambda = 1.55\mu m$, $r_{core} = 1.1\mu m$, $r_{centre} = 0.4\mu m$, $n_{core} = 1.480$, and $n_{clad} = 1.446$.

Fig.6 also illustrates the spectral dispersion of the 3.order modes (equivalent to LP_{02} modes in standard optical fibres), and we note that the dispersion curve is very close to the material dispersion for wavelengths above 1100 nm. The reason is that the 3.order mode has a cut-off wavelength of around 1.0μm and it is, therefore, not guided at wavelengths longer than this value. It should also be noted that the rather low 3.order mode cut-off wavelength compared to that of the 2.order modes is a consequence of the central void in fibres according to the present invention. The reason is that the 3.order modes normally have a local mode field intensity maximum in the centre of the fibre, but due to the low-index void the propagation of this mode distribution is discriminated. The figure also indicate that around its cut-off wavelength, the 3.order mode exhibits strong, negative dispersion and therefore also the 3.order mode may be utilized for dispersion and/or dispersion slope compensation. It is also worth noticing that the 3.order mode cut-off takes place at shorter wavelengths than the 2.order mode cut-off, hence for dispersion compensation at a given operational wavelength, the fibre must be scaled to larger dimensions when using the 3.order mode as compared to using the 2.order mode. This is an advantage in terms of realizing larger mode field diameters. Furthermore, from a production perspective, it is generally simpler to fabricate optical fibres incorporating holes at larger dimensions, and thus it may be further advantageous to realize dispersion compensating fibres using 3. or higher order modes.

The fibres according to the present invention provide a very wide range of freedom concerning parameter choice and obtainable fibre properties. To demonstrate some of these potential possibilities, Fig.7 illustrates corresponding values of dispersion (in ps/km/nm) and dispersion slope (in ps/km/nm^2) calculated (by a scalar approximation) for the LP_{11} mode in various implementations of HOM-DC-PCF fibres according to the present

invention. The considered fibre designs are of the type indicated in Fig.4, and we note that very low dispersion values (down to –2000 ps/km/nm - or even lower for specific parameter combinations) are predicted. It is also important to notice that a wide range of dispersion slope values are covered (both negative and positive), so fibres according to the present invention are capable of performing effective dispersion compensation combined with a wide range of dispersion slope compensation corresponding to specific system requirements.

The present inventors have furthermore realised that additional placement of voids (or microstructures) in the fibre cross section may not only further discriminate the relative guiding strength (and thereby the attenuation of the propagating mode), but also provide strongly enhanced spectral variations on the effective refractive indices of the higher-order modes in question. Therefore, by using microstructured sections of the fibre cladding and at the same time controlling the dimensions of a central void, strongly improved higher-order mode dispersion values may be obtained. This is on one side in contrast to the expectations that one would have considering the fundamental mode of a fibre with a central void, because the spreading of the mode field to some degree has weakened our ability to obtain a spectrally strong variation with respect to the effective index. Numerical studies of microstructured single-mode optical fibres with a central void supports this viewpoint. On the other side, higher-order-mode dispersion-compensating fibres made from standard fibre technology generally have a highly doped central core (as schematically indicated in Fig.2), so a central void is not natural in these cases.

In Fig.8a we illustrate a preferred embodiment of a higher-order mode dispersion compensating photonic crystal fibre (HOM-DC-PCF) according to the invention. This example of a microstructured fibre which guides higher-order modes is characterized by:

- a central void (80)
- a core section (81), which is realised by a material choice (typically doping – and in silica fibres generally Ge- and/or Al-doping) in a section adjacent to the central void
- an inner cladding region comprising low-index features (82) (typically voids) that extend in the longitudinal direction of the fibre and are placed in a background material (83) of the inner cladding, the inner cladding having an effective refractive index, $n_{clad,inner,eff}$
- and an outer cladding region (84) that may optionally comprises features, the outer cladding having an effective refractive index, $n_{clad,outer,eff}$ being higher than $n_{clad,inner,eff}$.

In preferred embodiments the core region has an annular shape. It may be preferred that the core region has a uniform index profile or that the core has a given cross-sectional variation in its refractive index (e.g. a radial variation). Also, it may be preferred that the core region comprises features that extend in the longitudinal direction of the fibre – as will be discussed in a proceeding section. It may also be preferred that the background material of the inner and the outer cladding regions is identical, for example un-doped, fused silica. In the present example the voids (82) are placed in predominantly equal distance to the fibre centre. Generally, the outer cladding (84) serves to optically isolate the core region and inner cladding region from the outside of the fibre as well as to provide strength and handle ability. It should be noted that the microstructured part of the fibre (the inner cladding region) in the illustration consist of a somewhat arbitrarily chosen number of 19 voids (82), however this number is in no manner a requirement and fewer of more voids could have been used. The key point is that the microstructured part of the fibre should provide a significant – and generally much stronger – index suppression than obtainable with standard fibre doping techniques, and hereby allow for the higher-order mode to experience the desired effective index variation as a function of wavelength. In contrast to standard HOM-DCFs, the microstructured part of the fibre will further allow for a significantly improved tailorability of the spectral dependency of the involved refractive index. The number of voids and their relative size and location are, therefore, important design parameters, and they may according to the present invention be varied. An example of such a design variation is shown in Fig.8b, in which the central void (85), and the high-index core (86) is surrounded by two layers of voids (87) placed in a background material. The two layers of voids form the inner cladding region that is surrounded by a solid outer cladding region.

The present inventors have investigated various fibres according to the invention. As an example, a fibre with a design as schematically shown in Fig. 9 has been analysed. The fibre is characterized by a central feature (90) surrounded by a high-index region (91) forming the fibre core and a micro-structured cladding comprising low-index features (92) and a background cladding material (93). The central feature has a diameter d_{center}, and a minimum refractive index n_{center}. The core region (91) has an inner diameter $d_{core,inner}$ being equal to d_{center} and an outer diameter $d_{core,outer}$, and the core comprises material with a refractive index n_{core}. The cladding features have a diameter d_{clad}, a typical centre-to-centre spacing, Λ, and the cladding comprises material with a refractive index n_{clad}, whereas the background material has a refractive

index $n_{clad,back}$. Preferably, the fibre comprises silica-based material and/or polymer material. Hence, often n_{core} and $n_{clad,back}$ is in than range from 1.42 to 1.50 (for silica) or from 1.30 to 1.90 or higher (for polymers). Typically, the cladding features and the central feature are voids, hence n_{center} and n_{clad} are around 1.0. The fibre may naturally be post-processed to render the voids filled up with materials of various refractive indices. When stating that the core comprises material with a given refractive index, this also covers that the core regions has an index variation in the cross-section, such as a given profile for example a step-index profile, where the a maximum refractive index value is given by n_{core}. A broad range of other profiles, such as for example parabolic index profiles are also of interest. The above-stated arguments naturally is also valid for the refractive index of the central features and the various cladding regions and features.

The present inventors have analysed various values of the above-mentioned design parameters for fibres. Generally, the present inventors have found that it is advantageous with respect to dispersion properties that the central void has a larger size than the cladding features, hence that d_{center} is larger than d_{cl}. Fig. 10 shows an illustration of mode indices (1., 2. and 3.order modes and equivalent core and cladding effective indices) for a fibre with a design as schematically shown in Fig. 9 that has the following design parameters: $d_{center} = 1.8\mu m$, $d_{core} = 3.0\mu m$, $d_{clad} = 1.2\mu m$, $\Lambda = 3.0\mu m$, $n_{center} = 1.000$, $n_{core} = 1.470$, and $n_{clad,back} = 1.444$, and $d_{core,inner} = d_{center}$ ($d_{clad}/\Lambda = 0.4$, $d_{center}/\Lambda = 0.6$). Fig. 10 aids for an understanding of the operation of fibres according to the present invention. The figure illustrates the mode indices of the fundamental (label 'Eig. #1') and two higher order modes (label 'Eig. #4' refers to the second-order mode and label 'Eig. #9' refers to the third-order mode). The figure furthermore illustrates the effective indices of two full-periodic structures approximating an equivalent cladding index (labelled 'd/Pitch=0.4, n=1.444') and an equivalent 'centre+core' index (label 'd/Pitch=0.6, n=1.470'). The equivalent cladding index is introduced to make an approximation of the effective cladding index of the fibre and the effective cladding index is approximated by a full-periodic, triangular structure having a background index of 1.444 and air holes with a diameter of 0.4Λ. Accordingly, the effective 'center+core' index is approximated by a full-periodic, triangular structure having a background index of 1.470 and air holes with a diameter of 0.6Λ. As seen from the figure, the second and third order modes have an abrupt behaviour at wavelengths around 1.3μm and 0.9μm, respectively. This corresponds

to the wavelength ranges where the two respective higher order modes have their cut-offs and may become guided by total internal reflection (their mode index increase above the effective cladding index). An abrupt behaviour in mode index results in strong dispersion, and the fibre is, therefore, seen to provide means for realizing strong dispersion by guiding light in one of the higher order modes. It is important to notice, that the fundamental mode does not exhibit an abrupt behaviour and in according with previous arguments, the fibre design having a void in the centre is not advantageous for providing strong dispersion in the fundamental mode. For specific dispersion compensating applications it is, therefore, desired to design the fibre such that the abrupt behaviour of one of the higher-order modes takes place at a predetermined, desired wavelength of operation. For dispersion compensation using the 2.order mode at a wavelength around 1.55μm, the dimensions of the here-discussed fibre should, therefore, be scaled up by a factor of approximately 1.55/1.3=1.2 – resulting in Λ of around 3.5μm (and the other dimension parameters scaled similarly). For operation using the 3.order mode, the scaling factor would accordingly be around 1.7 – resulting in Λ of around 5.2μm. Typical dispersion values that are obtained for fibres with a design as the one discussed here is more negative than –200ps/nm/km for the 2.order mode and more negative than –1000ps/nm/km for the 3.order mode.

Generally, the number of modes that a fibre may guide at a given wavelength is determined by the available mode-space. The mode-space is related to the core area and the refractive index difference between the core and its surroundings. Hence, for fibres according to the present invention, the number of modes – and thereby the ability to guide a higher-order mode – is related to the parameters: $n_{centre,eff}$, $n_{core,eff}$, $n_{clad,eff}$, r_{centre}, $r_{core,outer}$, and λ, where λ is the operating wavelength.

The normalized frequency, V, has previously been discussed as a tool for determining the cut-off for step-index fibres. For fibres according to the present invention, a more general effective normalized frequency may, as a first approximation, be written as:

$$V_{eq,eff} = k(r_{core}{}^2 - r_{centre}{}^2)^{½}(n_{core,eff}{}^2 - n_{clad,eff}{}^2)^{½} ,$$

where k is the free-space wave number equal to $2\pi/\lambda$ (λ is the free-space optical wavelength for the operation of the fibre), r_{core} is the core radius (or a maximum radial dimension in the case of non-circular core geometry) and r_{centre} is the radius of the central region (or a maximum radial dimension in the case of non-circular centre geometry), and $n_{core,eff}$ and $n_{clad,eff}$ is the core and cladding effective refractive index, respectively. As previously discussed, this approximation, however, neglects the refractive index difference

between the core region and the centre region (the approximation is therefore most appropriate in the case of a fibre having a centre region similar to the cladding region). The core-centre index difference is typically larger than the index difference between the core and the cladding – and therefore effectively provides a stronger confinement to the core than predicted by the $V_{eq,eff}$ expression when comparing to a standard, step-index fibre of similar V-value. In other words, the fibre core has, in fact, a larger mode-space than predicted by the Veq,eff expression, for $n_{centre,eff}$ lower than $n_{clad,eff}$ and the fibre may, therefore, support higher-order modes at a lower $V_{eq,eff}$ value than for a fibre with a centre region having similar refractive index as the cladding region. A more appropriate expression of V has not been deduced and, therefore, an accurate lower limit of V for multi-mode operation may not be given. However, a $V_{eq,eff}$ value of around 1.2 is considered representative as a lower value providing multi-mode operation of fibres according to the present invention in the case of n_{centre} around 1.0. For n_{centre} approaching $n_{clad,eff}$, the Veq,eff value at the cut-off will approach 2.1.

As various refractive index profiles or/and various types of microstructuring may be used for the various regions in a fibre, the above-mentioned given value may not be equal to that found for standard, step-index fibres, namely 2.14. Looking at Fig. 10, for example, it is found that $V_{eq,eff}$ is equal to approximately 1.86 at the cut-off of the first higher-order mode. The parameters used for the calculation of $V_{eq,eff}$ are: λ=1.16μm, r_{core}=1.5μm, r_{centre}=0.9μm, $n_{core,eff}$=1.470 (the core is homogeneous in this example), and $n_{clad,eff}$=1.442 (the effective refractive index of the cladding is found from the curves labelled 'd/Pitch=0.4, n=1.444' in Fig. 10).

Hence, for a fibre according to the present invention with $V_{eq,eff}$ around 1.86 or higher, higher-order modes may be supported. For use as dispersion compensating fibre, the fibre is to be operated close to the cut-off of a higher-order mode, hence, it is preferred that the fibre has $V_{eq,eff}$ around 1.86 for operation at the first higher-order mode. For operation at the second higher-order mode (λ of around 900nm), $V_{eq,eff}$ is around 2.35.

For a fibre according to the present invention to be able to support a higher-order mode, it is, therefore, required that $V_{eq,eff}$ is around or higher than at least 1.2, such as at least 1.5, such as at least 1.8, such as at least 2.1, such as at least 2.5.

In a further preferred embodiment, the doping of the fibre material may be avoided. An example of such a design cross section is shown in Fig.11a in which a central void (110) is surrounded by an un-doped core region of the optical fibre (111) in which no voids are placed. The effective index of the core region (111) is, however, still higher than the effective index of the inner cladding region that comprises low-index features (112) – here shown in a close-packed configuration as an example. The background material of the inner cladding region (113) and the background material in the core region (111) is in this example identical. The fibre also comprises an outer cladding region (114) with similar effective refractive index as the core region. The invention is, however, not limited to this configuration and numerous variations and even deviations from a periodic structure may be shown efficient. It is important to notice that the key point is to form a ring shaped high-index section that may provide index volume that “fits” the modal shape of the higher-order (typically LP_{11}-like) mode. In the previous examples, this was obtained by doping or combinations of doping and microstructuring, but as in the case of Fig.9 it may also be obtained simply by microstructuring to lower the effective refractive index of the inner cladding. It may also for certain applications be advantageous to have dopants that locally lower the refractive index or additional microstructuring in the core region of the fibre.

In a further preferred embodiment - such as the one illustrated in Fig.11b - the central void (115) is surrounded by an un-doped core region (116), but in contrast to the previous example, the inner cladding region comprises two layers, where the first layer comprises voids (117) of larger dimensions than the voids (118) present in the second layer. The fibre again comprises a solid outer cladding region (119). It is noted that the first layer has a lower effective refractive index than the second layer due to the larger size of the voids (117) compared to the voids (118). The present inventors have realized that this relation between the void sizes in the inner cladding region enhances the ability to obtain large dispersion compensation in a higher order mode. The larger inner cladding features provide effectively an inner cladding with a depressed refractive index. This results in a more abrupt cut-off of the higher order modes – and thereby improves the possibility of realizing strong (negative) dispersion.

Another example of combining doped and microstructured sections of the fibres according to the present invention is shown in Fig.12, where a cross-section of the fibre is illustrated. The fibre structure is formed by a central void (120) surrounded by a doped annular ring

(121) forming the core. The core (121) is surrounded by a microstructured annular section (122). Further away from the fibre centre, an additional doped index ring (123) is included, and the fibre further comprises a cladding (124) of predominantly homogeneous material. It should be noted that numerous combinations are possible both with respect of combining index raised and index lowered sections and with respect to the use of spectral mode shaping through control of microstructured sections.

In the previous part of this application, several preferred embodiments of fibres according to the invention have been shown. Common for these is the aim of favouring the waveguiding properties of higher-order modes while ensuring a high spectral variation of the effective refractive index experienced by these modes. A key element in these designs have been the ability to locate index raised sections, where the mode intensity – and thereby the impact – is largest. Following these guidelines, an additional aspect of the invention appears when we consider the "two-lobe" structure of the LP_{11} higher-order modes. In agreement with our argumentation it will be advantageous to adapt the index distribution to this lobe structure of the LP_{11} mode, which means that we should aim for core regions with non-circular symmetric distributed effective index. A preferred embodiment of such a fibre design is schematically illustrated in Fig.13. In this example of a fibre according to the present invention, the fibre design is tailored for enhancing the waveguiding properties of specifically oriented higher order modes using high-index features in the core region. In comparison with Fig. 4, the core region comprises two high-index features (131) that are placed at positions favouring the propagation of a two-lobed higher order mode, such as the 2.order mode LP_{02}. The fibre is characterized by the central void (130) having a lower refractive index than any material adjacent to the void. The central void (130) is surrounded by a core region having a core background material (133) with refractive index $n_{core,back}$ and features (131) with a refractive index n_{core} being larger than $n_{core,back}$. The fibre has a cladding comprising an inner cladding region (164) and an outer cladding region (135). The inner cladding region (134) has a lower refractive index than the core background material (133) and optionally lower than the outer cladding region (134). The distance (132) is preferably in the range from 3.0μm to 20.0μm. Alternatively, the inner cladding region (134) may be substituted with a ring-shape region comprising microstructured features (140), such as shown schematically in Fig. 14.

Another example of a fibre according to the present invention, that has been tailored for the mode shape of a higher-order mode is shown in Fig. 15. Here the central void (150) is located within a base material (152) in which voids (151) forms microstructured sections. Note that the microstructured part of the illustrated example is placed at two opposite sides of the central void. In other sections of the fibre core (153) a homogeneous material is located having a lower refractive index than (152). The fibre is finally consisting of an outer cladding (154), which in addition may include further microstructuring or doping, but in the present illustration the cladding is considered to be of a homogeneous un-doped material.

Another example of a fibre according to the present invention is shown schematically in Fig. 16. The fibre guides light in a higher order mode and it is characterized by a core region (161) having a rectangular shape. The fibre has furthermore an inner cladding comprising two regions comprising microstructured features (160) placed in a background material (162).

Another method for enhancing the waveguiding properties of specifically oriented higher order modes is indicated in Fig.17, where an elliptically shaped central void (170) is surrounded by a – also elliptically shaped – raised index section (171). This waveguide also consists of a cladding (172), which in addition may include microstructured sections (not illustrated in this figure).

When we consider the application of HOM-DC-PCFs it is a key issue to evaluate the possibilities for manufacturing highly effective mode converters on the input and output ends of the dispersion compensating fibre-sections. Especially in the cases, where we apply aspects of the invention in which the refractive index profiles are strongly non-circular symmetric, it will be essential to ensure mode coupling to the correct orientation of the higher order modes. It is, however, an advantage that preferred embodiments of the present invention allows for accurate control of these properties. The central point is to make use of the possibility that non-circular symmetrically placed sections of the fibre cross sections may be designed to have significantly different photo sensitivity. As schematically illustrated in Fig.18, a mode converter (180) in the input end of the HOM-DC-PCF is formed by direct UV writing in

the non-circular symmetrically distributed photosensitivity of the fibre itself. After mode conversion the optical signal propagates through the dispersion compensating section (181), whereafter it is converted back into the fundamental LP_{01} mode of the transmission fibre in the output mode converter (182), which is realised in the same manner as the input mode converter. The illustration in Fig.18 indicates the non-circular symmetrically distributed photosensitive elements as the two bars (183), however, these should only be seen as the sections of the fibre with the highest photosensitivity. The central void (184) is just indicated at the fibre end, and the UV induced index raised sections have been indicated at the input end (185) and output end (186) of the optical fibre component.

Fibres according to the present invention having a central void and a raised index annular section surrounding the void have the advantage of providing improved splicing performance, when spliced to standard optical fibres using fusion splicing. One of the problems involved in splicing of microstructured fibres of pure silica is that the voids may collapse as the PCF is heated. As illustrated in Fig.19 the central void (193) (and possible additional voids in microstructured sections of the PCF) may collapse, but due to the raised index in the annular section of the fibre the heated section (191) may still maintain an index-guiding core. In contrast to this, pure silica fibres may have no waveguiding and mode confining sections close to a fusion splice, if all the voids are collapsed. Fig.19 schematically illustrates how the microstructured fibre (190) is spliced to a standard optical fibre (192).

In order to fabricate fibres according to the present invention, a technique well known for fabrication of microstructured fibres may be employed. The method is based on stacking of capillary tubes and rods to form a preform and drawing this into fibre using a conventional drawing tower and is has been well described in literature – see e.g. previous Birks et al. references. The present invention also covers designs of preforms, and an example of a preform according to the present invention is illustrated in Fig. 20. The preform comprises a centrally placed capillary tube (200) that is surrounded by a number of capillary tubes (202). The ensemble of capillary tubes are placed in a large overcladding tube (204). The central tube is made from a material having a higher refractive index compared to the refractive index of the material of the surrounding capillary tubes. When drawn to fibre, the central tube provides a void in the center of the fibre – from the void (201) – and its

background material provides an annular region serving as the fibre core. The capillary tubes (202) will provide the inner cladding of the fibre – an inner cladding that is microstructured by the voids (203). The overcladding tube (204) will provide the outer cladding of the drawn fibre that will serve mainly for mechanical robustness. A broad range of rods, tubes or a combination of these may also form the preform. During drawing, the voids (201) and (203) may preferably be controlled using various types of gas pressurizing techniques to yield any desired final sizes of the voids in the fibre. A fibre with a design as schematically shown in Fig. 14 may for example be fabricated from a preform as schematically shown in Fig. 21 having a combinations of solid silica tubes (210) of high refractive index and solid canes (211) and tubes (212) of lower refractive index. A fibre with a design as schematically shown in Fig. 17 may for example be fabricated from a preform as schematically shown in Fig. 22 having a central capillary tube (220) of high refractive index, two neighbouring capillary tbes (221) and (222), a number of solid rods (223) and an overcladding tube (224). During drawing, an over pressure may be applied to the tube (220) and the tubes (221) and (222) may be collapsed (using an under-pressure) to yield a non-circular shape of the central void in the final fibre. The fibres schematically shown in Fig. 15 and 16 may be fabricated using for example a number of non-circular tubes and/or rods where the non-circularity of the individual tubes/rods have been obtained using for example mechanical polishing.

To fabricate microstructured fibres according to the present invention, further information on the drawing process may be found in the international literature including the patent literature, see for example previously mentioned DiGiovanni et al. reference.

It will be apparent to those skilled in the art that various modifications and variations of the present invention can be made without departing from the spirit and scope of the invention. Thus, it is intended that the present invention include the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.

CLAIMS

1. An optical fibre with a waveguide structure for supporting the transmission of light at a predetermined or operating wavelength λ_0, said optical fibre having a longitudinal direction and a cross-section perpendicular to said longitudinal direction, said optical fibre comprising:

- a central region having a centre axis in said longitudinal direction, said central region extending along and including said centre axis, said central region having an outer periphery with a maximum distance to the centre axis $r_{centre,max}$, a minimum refractive index $n_{centre,min}$, an effective refractive index $n_{centre,eff}$ and/or a resultant geometrical index $n_{g,centre}$,

- a core region extending along said longitudinal direction and surrounding said central region, said core region having an inner periphery that coincides with the outer periphery of the central region, an outer periphery with a maximum distance to the centre axis $r_{core,max}$, a maximum refractive index $n_{core,max}$, an effective refractive index $n_{core,eff}$ and/or a resultant geometrical index $n_{g,core}$,

- a cladding region extending along said longitudinal direction, said cladding region surrounding and neighbouring said core region, said cladding region having an inner periphery that coincides with the outer periphery of the core region, an outer periphery with a maximum distance to the centre axis $r_{cladding,max}$, a maximum refractive index $n_{clad,max}$, an effective refractive index $n_{clad,eff}$ and/or a resultant geometrical index $n_{g,clad}$,

wherein $n_{centre,eff}$ is equal to or lower than $n_{clad,eff}$ and $n_{clad,eff}$ is lower than $n_{core,eff}$ at the wavelength λ_o, and/or wherein $n_{g,centre}$ is equal to or lower than $n_{g,clad}$ and $n_{g,clad}$ is lower than $n_{g,core}$ at the wavelength λ_o.

2. An optical fibre according to claim 1, wherein $n_{clad,eff}$, $n_{core,eff}$, $r_{centre,max}$, $r_{core,max}$ and λ_o are adapted to ensure that the fibre supports at least one higher order mode.

3. An optical fibre according to claim 1, wherein $n_{g,clad}$, $n_{g,core}$, $r_{centre,max}$, $r_{core,max}$ and λ_o are adapted to ensure that the fibre supports at least one higher order mode.

4. An optical fibre according to claim 1 or 2, wherein $n_{clad,eff}$, $n_{core,eff}$, $r_{centre,max}$, $r_{core,max}$ and λ_o are adapted or selected such that V_{eq} defined as

$$V_{eq} = (2\pi/\lambda_o)(r_{core,max}{}^2 - r_{centre,max}{}^2)^{½}(n_{core,eff}{}^2 - n_{clad,eff}{}^2)^{½}$$

is larger than or equal to 1.2 or larger than or equal to 1.5, and $n_{centre,eff}$ is equal to or lower than $n_{clad,eff}$ in order for said optical fibre to guide light in a higher order mode at said predetermined wavelength, λ_o.

5. An optical fibre according to claim 4, wherein V_{eq} is larger than or equal to 1.8 or larger than or equal to 2.1.

6. An optical fibre according to claim 4 or 5, wherein V_{eq} is larger than or equal to 2.5.

7. An optical fibre according to claim 1 or 3, wherein $n_{g,core}$, $n_{g,clad}$, $r_{centre,max}$, $r_{core,max}$ and λ_o are adapted or selected such that V_{eq} defined as

$$V_{eq} = (2\pi/\lambda_o)(r_{core,max}{}^2 - r_{centre,max}{}^2)^{½}(n_{g,core}{}^2 - n_{g,clad}{}^2)^{½}$$

is larger than or equal to 1.2 or larger than or equal to 1.5, and $n_{g,centre}$ is equal to or lower than $n_{g,clad}$ in order for said optical fibre to guide light in a higher order mode at said predetermined wavelength, λ_o.

8. An optical fibre according to claim 7, wherein V_{eq} is larger than or equal to 1.8 or larger than or equal to 2.1.

9. An optical fibre according to claim 7 or 8, wherein V_{eq} is larger than or equal to 2.5.

10. An optical fibre according to any of the preceding claims, wherein at least one of the peripheries of the central and the core regions is substantially elliptical.

11. An optical fibre according to any of the preceding claims, wherein at least one of the peripheries of the central and the core regions is substantially circular.

12. An optical fibre according to any of the preceding claims, wherein at least one of the peripheries of the central and the core regions is substantially rectangular.

13. An optical fibre according to any of the preceding claims, wherein said core region comprises a core background material with a refractive index $n_{core,back,O}$, which is uniform within process variations in a given cross section.

14. An optical fibre according to any of the preceding claims, wherein said cladding region comprises a cladding background material with a refractive index $n_{cladding,back,O}$, which is uniform within process variations in a given cross section.

15. An optical fibre according to any of the claims 1-13, wherein said cladding region comprises an inner cladding region and an outer cladding region surrounding said inner cladding region, wherein said inner and outer cladding regions have geometrical refractive indices in said cross-section of $n_{g,inner\ cladding}$ and $n_{g,outer\ cladding}$, respectively, where
$n_{g,inner\ cladding} < n_{g,core}$, or wherein said inner and outer cladding regions have effective refractive indices in said cross-section of $n_{eff,inner\ cladding}$ and $n_{eff,outer\ cladding}$, respectively, where $n_{eff,inner\ cladding} < n_{eff,core}$.

16. An optical fibre according to claim 15, wherein $n_{g,inner\ cladding} < n_{g,outer\ cladding}$ in said cross-section, or wherein $n_{eff,inner\ cladding} < n_{eff,outer\ cladding}$ in said cross-section.

17. An optical fibre according to claim 15 or 16, wherein said inner cladding region comprises an inner cladding background material with a refractive index $n_{inner\ cladding,back,O}$, which is uniform within process variations in a given cross section.

18. An optical fibre according to claims 15-17, wherein said outer cladding region comprises an outer cladding background material with a refractive index $n_{outer\ cladding,back,O}$. which is uniform within process variations in a given cross section.

19. An optical fibre according to any of the preceding claims, wherein the central region is a void.

20. An optical fibre according to any of the preceding claims, wherein the central region comprises a fluid substance.

21. An optical fibre according to any of the preceding claims, wherein the relative difference in geometrical refractive index or in effective refractive index between the core region and the cladding region is larger than 0,5 % and the difference between the average outer radial dimension of the core and central region is larger than 2.3 times the predetermined wavelength λ_0.

22. An optical fibre according to any of the claims 1-20, wherein the relative difference in geometrical refractive index or in effective refractive index between the core region and the cladding region is larger than 1 % and the difference between the average outer radial dimension of the core and central region is larger than 1.7 times the predetermined wavelength λ_0.

23. An optical fibre according to any of the claims 1-20, wherein the relative difference in geometrical refractive index or in effective refractive index between the core region and the cladding region is larger than 2 % and the difference between the average outer radial dimension of the core and central regions is larger than 1.2 times the predetermined wavelength λ_0.

24. An optical fibre according to any of the preceding claims, wherein the predetermined wavelength or operating wavelength λ_0 is within the range from 1.3 μm to 1.7 μm.

25. An optical fibre according to any of the preceding claims, wherein the predetermined wavelength or operating wavelength λ_0 is within the range from 1.53 μm to 1.64 μm.

26. An optical fibre according to claims 15-25, wherein said inner cladding region comprises a plurality of spaced apart cladding elements located in a background inner cladding material, each cladding element having a centre and extending in said longitudinal direction, and having a refractive index $n_{clad,elem}$ being lower than a

refractive index $n_{inner\_cladding,back}$ of any background inner cladding material adjacent to the cladding elements in a given cross-section.

27. An optical fibre according to claim 26, wherein said cladding elements are arranged in a pattern, which ensures an at-most-two-fold rotational symmetry about said centre axis.

28. An optical fibre according to claim 26, wherein the cladding elements included in the inner cladding region are located in at least one layer around said core region.

29. An optical fibre according to claims 26-28, wherein said multitude of spaced apart cladding elements of the inner cladding region comprises cladding elements with at least two different cross-sectional areas, and wherein cladding elements of predominately equal cross-sectional areas are arranged within prescribed minimum and maximum distances from the centre of the fibre.

30. An optical fibre according to claim 26 or 27, wherein said multitude of spaced apart cladding elements are of equal cross sectional form and area, each having a centre and an average radial dimension $r_{clad,elem}$, and positioned in the inner cladding region with substantially equal centre to centre spacing Λ.

31. An optical fibre according to claims 26-30, wherein said multitude of spaced apart cladding elements comprise voids.

32. An optical fibre according to claims 26-31, wherein said multitude of spaced apart cladding elements comprise a fluid substance.

33. An optical fibre according to claims 26-32, wherein the refractive indices of the core $n_{core,back,0}$, the inner cladding background $n_{inner\ cladding,back,0}$ and the outer cladding background $n_{outer\ cladding,back,0}$ are uniform and equal within process variations in a given cross section.

34. An optical fibre according to claim 33 wherein the core and cladding material is undoped silica.

35. An optical fibre according to any of the claims 26-33, wherein the inner cladding region comprises one or more annular segments having a higher geometrical refractive index $n_{g,ann-seg}$ or a higher effective refractive index $n_{eff,ann-seg}$ than the refractive index of any inner cladding background material adjacent to it.

36. An optical fibre according to claim 35, wherein the higher geometrical or effective refractive index is achieved by doping.

37. An optical fibre according to any of the preceding claims wherein the core or cladding regions comprise silica glass.

38. An optical fibre according to any of the preceding claims wherein the core or cladding regions comprise a polymeric material.

39. An optical fibre according to claim 37 or 38 wherein all of or parts of the core or cladding regions are doped with one or more dopants from the group comprising Ge, F, P, Sn, Bm, Er, Yb, Nd, La, Ho, Dy, Tm and other rare-earth and transition metal ions.

40. An optical fibre according to any of the preceding claims, wherein said core region comprises one or more core elements located in a background core material and extending along said longitudinal direction, each of said one or more core elements having a centre and a refractive index $n_{core,elem}$ being higher than a refractive index of any background core material $n_{core,back}$ adjacent to the core element in a given cross-section.

41. An optical fibre according to claim 40, wherein said one or more core elements are fully enclosed by said background core material and individually spaced apart.

42. An optical fibre according to claim 40 or 41, wherein said one or more core elements are arranged in a pattern, which ensures an at-most-two-fold rotational symmetry about said centre axis.

43. An optical fibre according to any of the preceding claims, wherein said central region comprises undoped silica.

44. An optical fibre according to any of the preceding claims, wherein said central region comprises a polymeric material.

45. A dispersion compensating module comprising an input section, a length of fibre according to any of the claims 1-44 and an output section, said input section and said output section each containing a Bragg-grating structure, said input section being designed to perform mode conversion between a fundamental mode and a higher-order mode, and said output section being designed to perform mode conversion between said higher-order mode and said fundamental mode, and said length of fibre has a negative dispersion for said higher-order mode.

46. A preform for producing fibres according to claims 1-44, wherein an elongated cylindrical capillary centre tube being defining a centre axis and being made of a material with refractive index n_{cntt}, is stacked together with a multitude of N individual elongated cylindrical surrounding bodies being made of a material with refractive indices $n_{sb,i}$, $i = 1,2, \ldots, N$, said centre tube is centrally located among said surrounding bodies, and at least one circumfering tube being made of a material with refractive index $n_{circt,j}$ surrounding said centre tube and said surrounding bodies, said centre tube, said surrounding bodies and said circumfering tube are of substantially equal length,

47. A preform according to claim 46, wherein said surrounding bodies are identical capillary tubes being made of a material with refractive index n_{sb}, and the refractive index n_{cntt} of said centre tube is larger than the refractive index n_{sb} of said surrounding capillary tubes.

48. A preform according to claim 46, wherein said surrounding bodies comprise a mixture of one or more first identical rods being made of a material with refractive index $n_{sb,rod-1}$ and one or more second identical rods being made of a material with refractive index $n_{sb,rod-2}$ and one or more identical capillary tubes being made of a material with refractive index $n_{sb,cap-1}$.

49. A preform according to claim 48, wherein said one or more first identical rods include 2 rods placed adjacent to and on opposite sides of said centre tube, and the preform has an at-most-two-fold rotational symmetry about said centre axis.

50. A preform according to claim 56, wherein said surrounding bodies comprise a mixture of one or more first identical rods being made of a material with refractive index $n_{sb,rod-1}$ and one or more identical capillary tubes being made of a material with refractive index $n_{sb,cap-1}$.

51. A preform according to claim 50, wherein said one or more identical capillary tubes include 2 tubes placed adjacent to and on opposite sides of said centre tube, and the preform has an at-most-two-fold rotational symmetry about said centre axis.

Fig.1

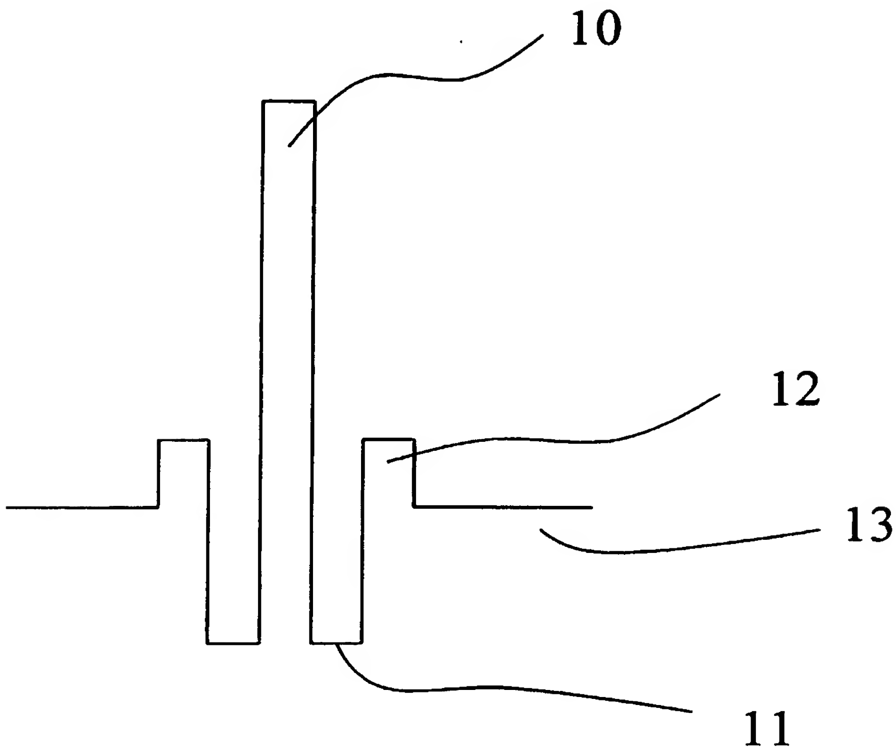


Fig.2

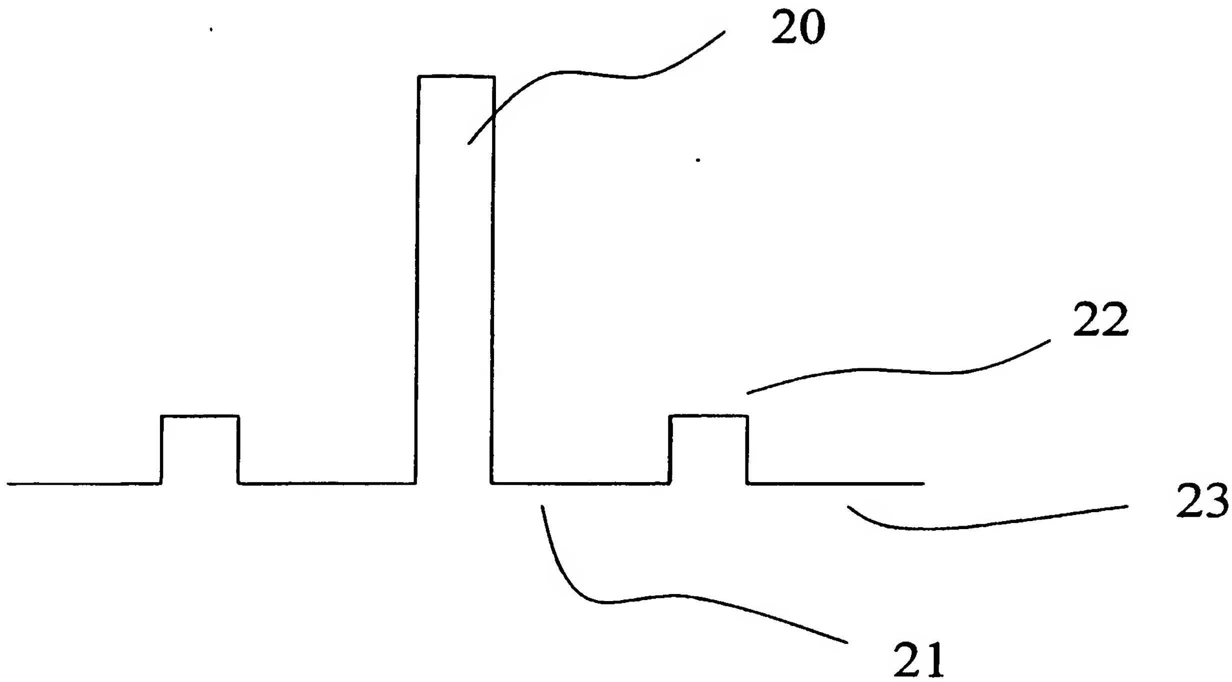


Fig.3

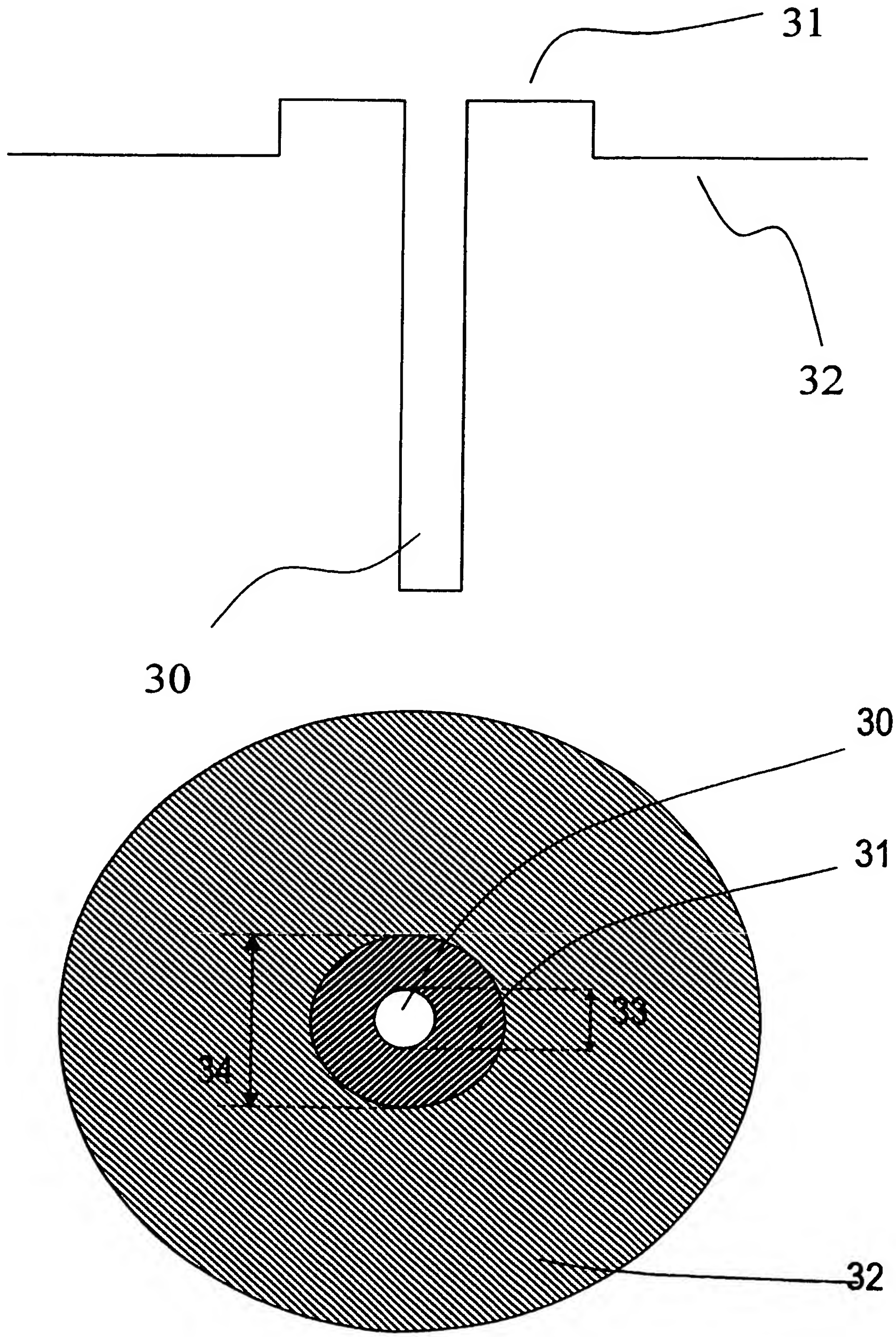


Fig.4

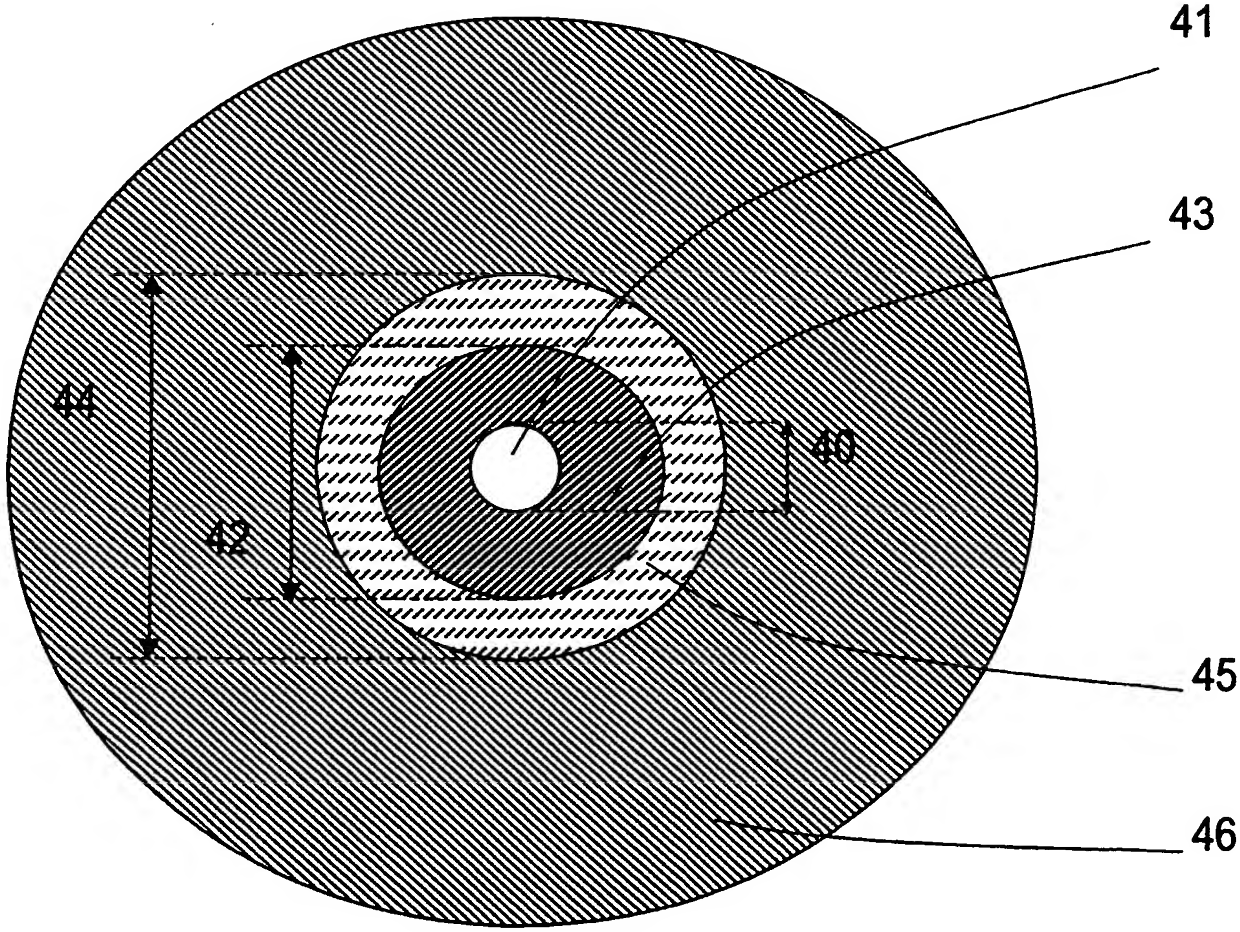
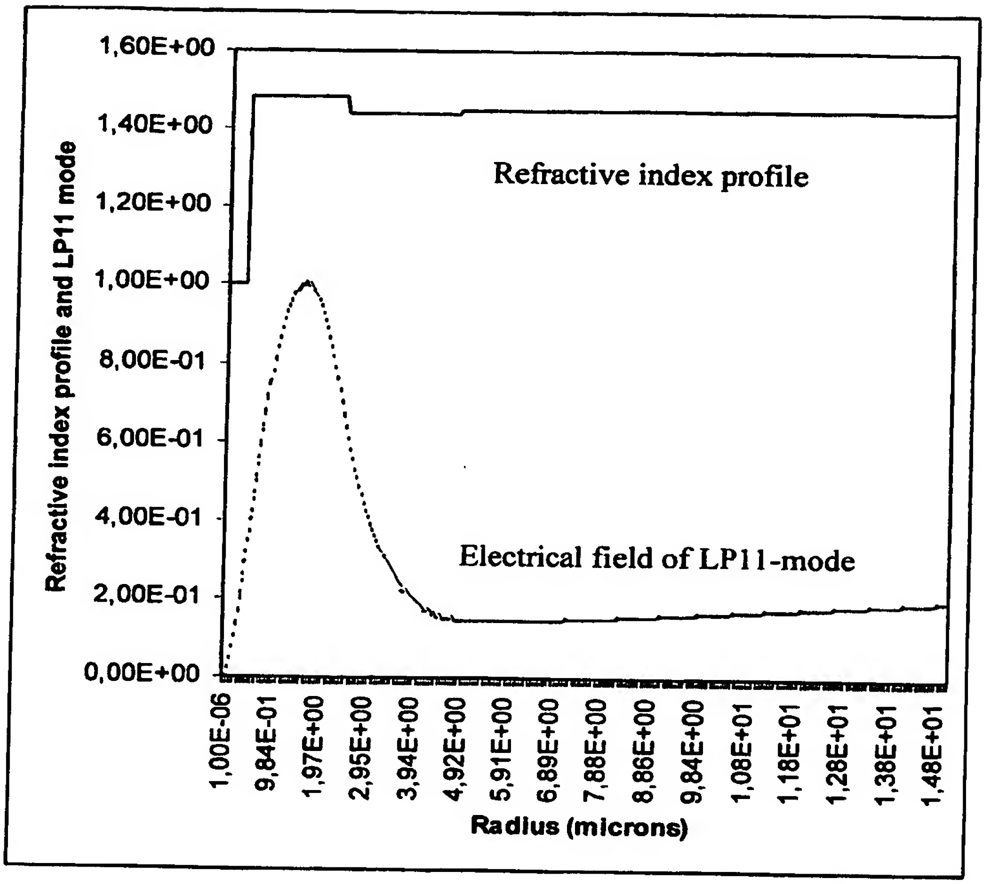


Fig.5



1,60E+00
1,40E+00
1,20E+00
1,00E+00
8,00E-01
6,00E-01
4,00E-01
2,00E-01
0,00E+00
Refractive index profile and LP11 mode
Refractive index profile
Electrical field of LP11-mode
1,00E-06
9,84E-01
1,97E+00
2,95E+00
3,94E+00
4,92E+00
5,91E+00
6,89E+00
7,88E+00
8,86E+00
9,84E+00
1,08E+01
1,18E+01
1,28E+01
1,38E+01
1,48E+01
Radius (microns)

Fig.6

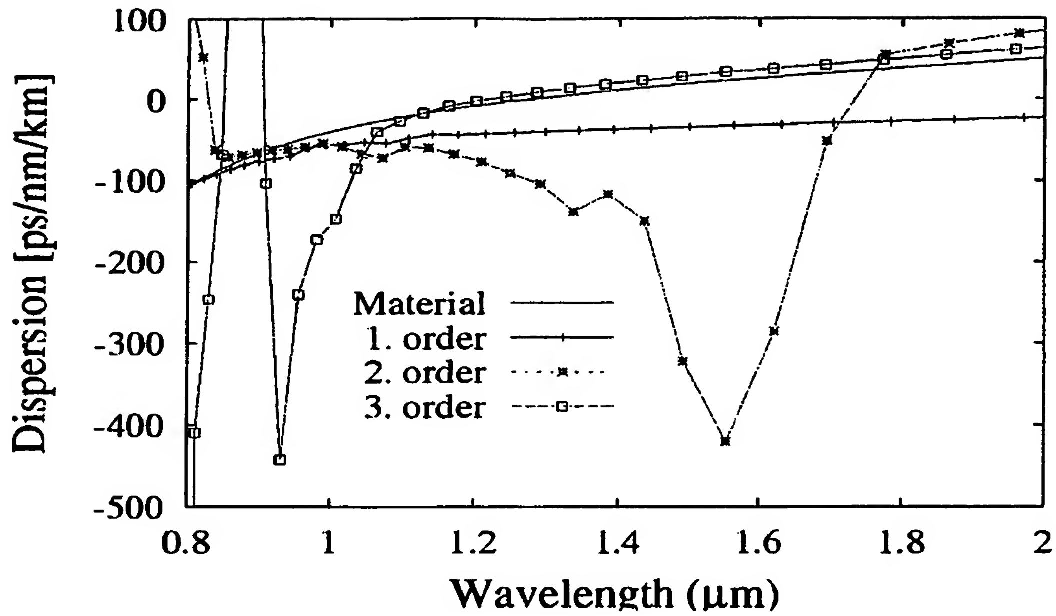

100
0
-100
-200
-300
-400
-500
Dispersion [ps/nm/km]
0.8
1
1.2
1.4
1.6
1.8
2
Wavelength (μm)
Material
1. order
2. order
3. order

Fig.7

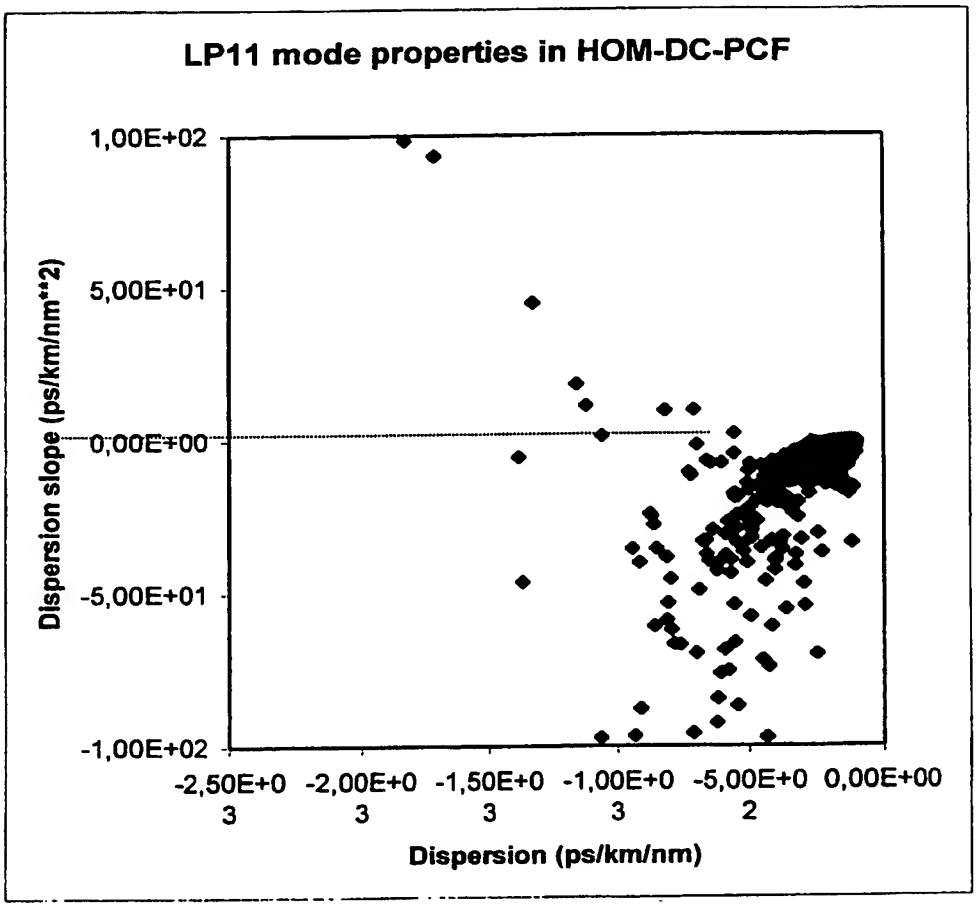

LP11 mode properties in HOM-DC-PCF
1,00E+02
5,00E+01
0,00E+00
-5,00E+01
-1,00E+02
Dispersion slope (ps/km/nm**2)
-2,50E+03
-2,00E+03
-1,50E+03
-1,00E+03
-5,00E+02
0,00E+00
Dispersion (ps/km/nm)

Fig.8a

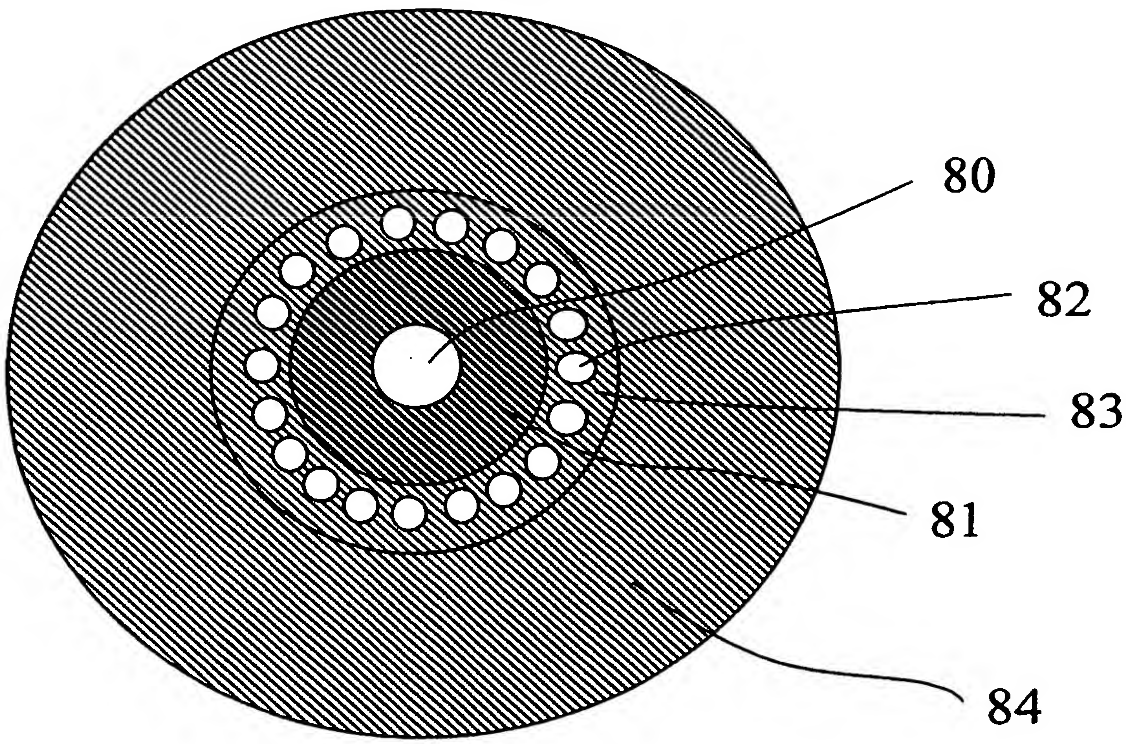


Fig.8b

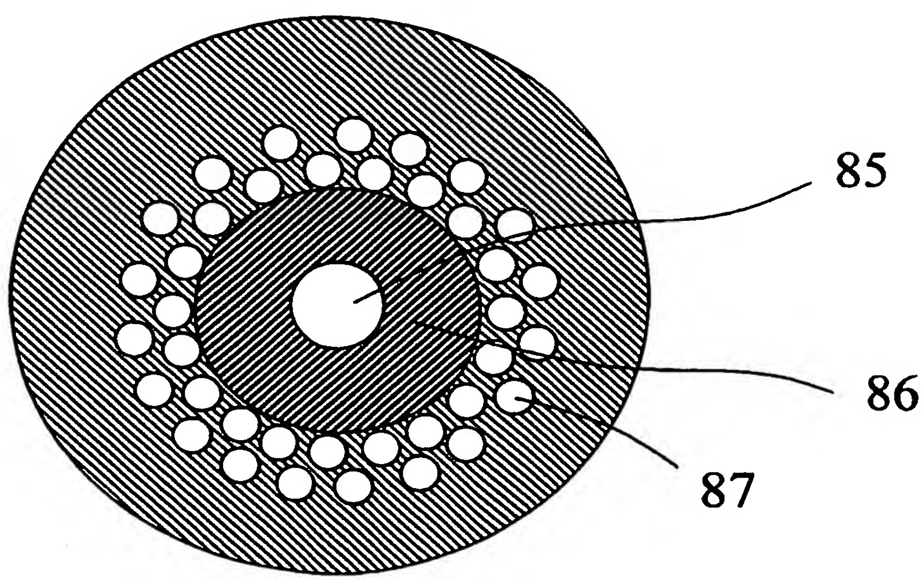


Fig.9

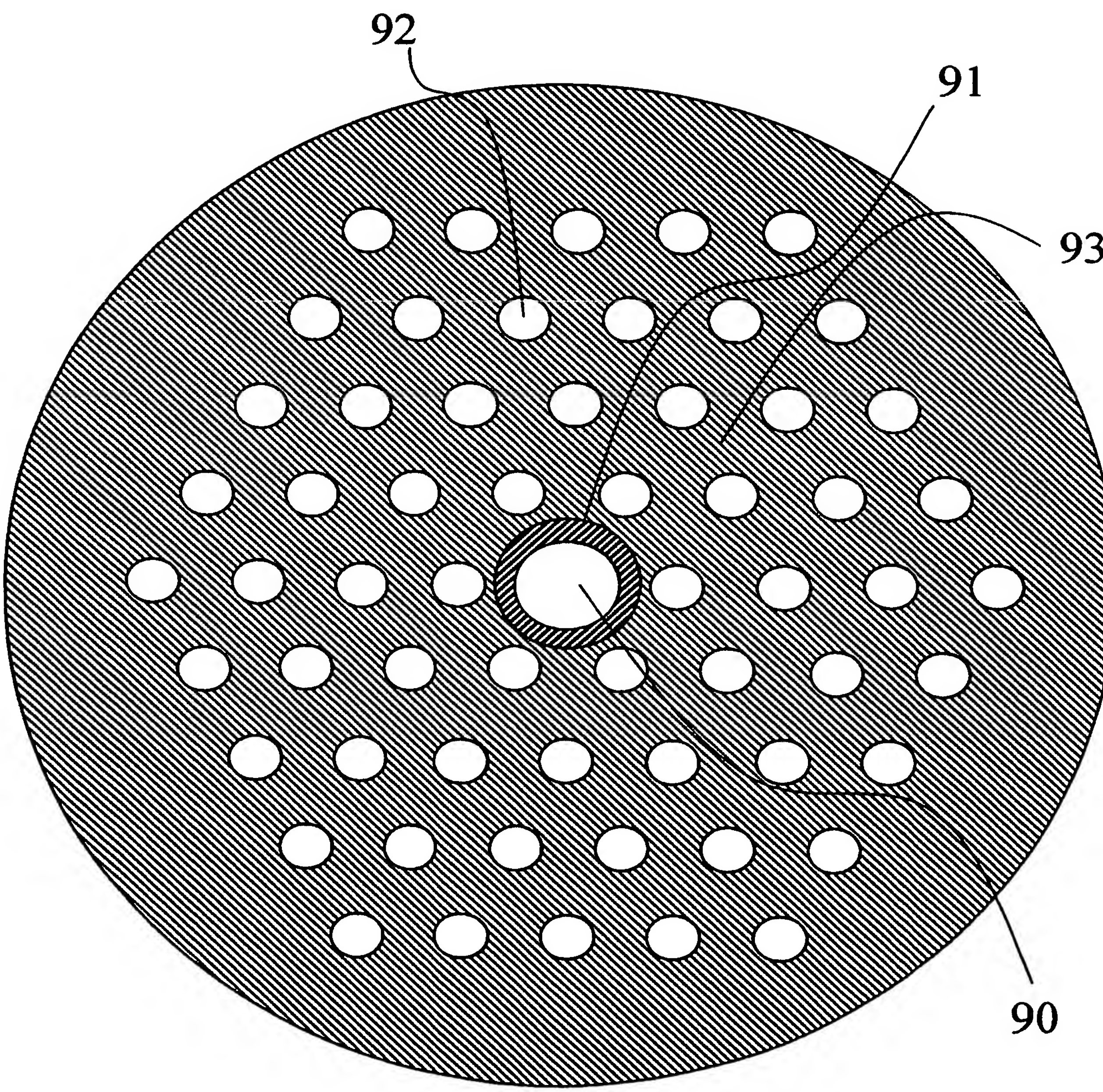
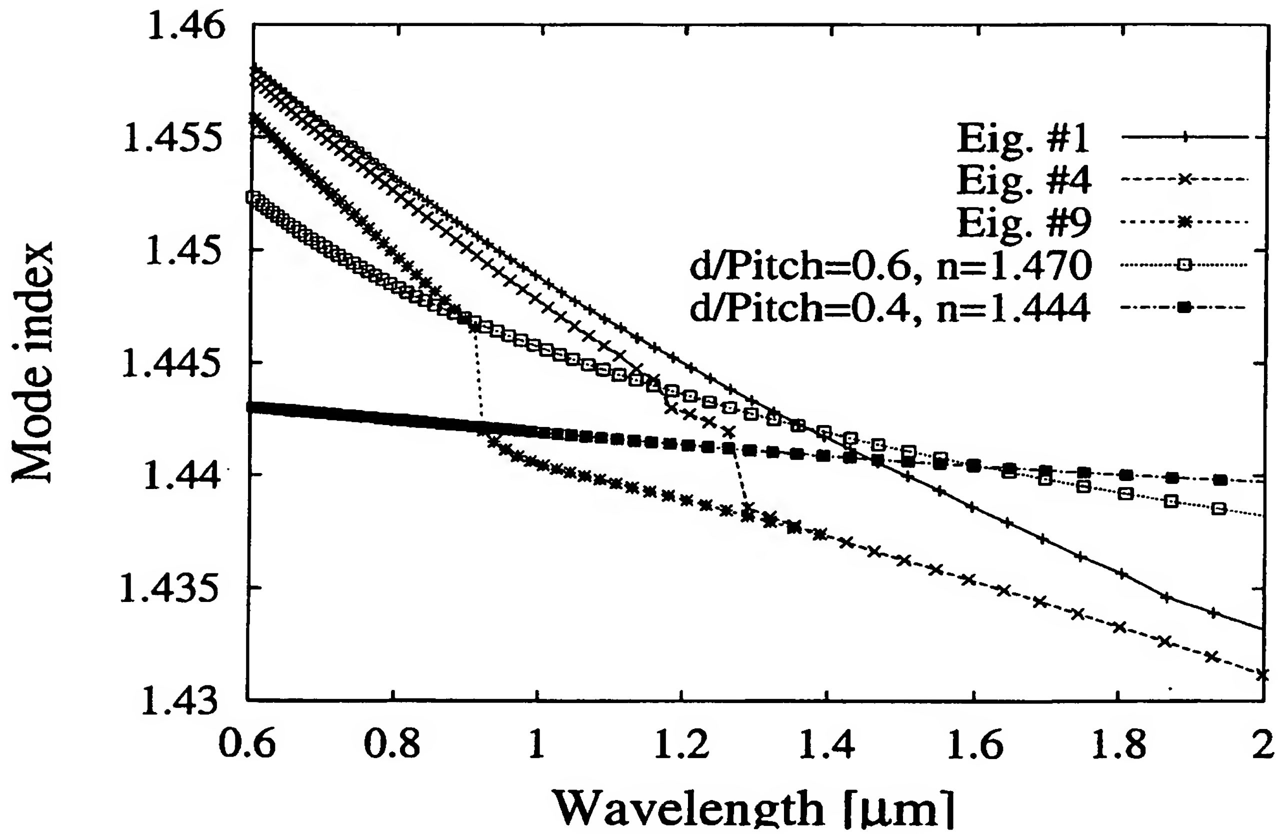


Fig. 10



1.46
1.455
1.45
1.445
1.44
1.435
1.43
Mode index
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Wavelength [μm]
Eig. #1
Eig. #4
Eig. #9
d/Pitch=0.6, n=1.470
d/Pitch=0.4, n=1.444

Fig.11a

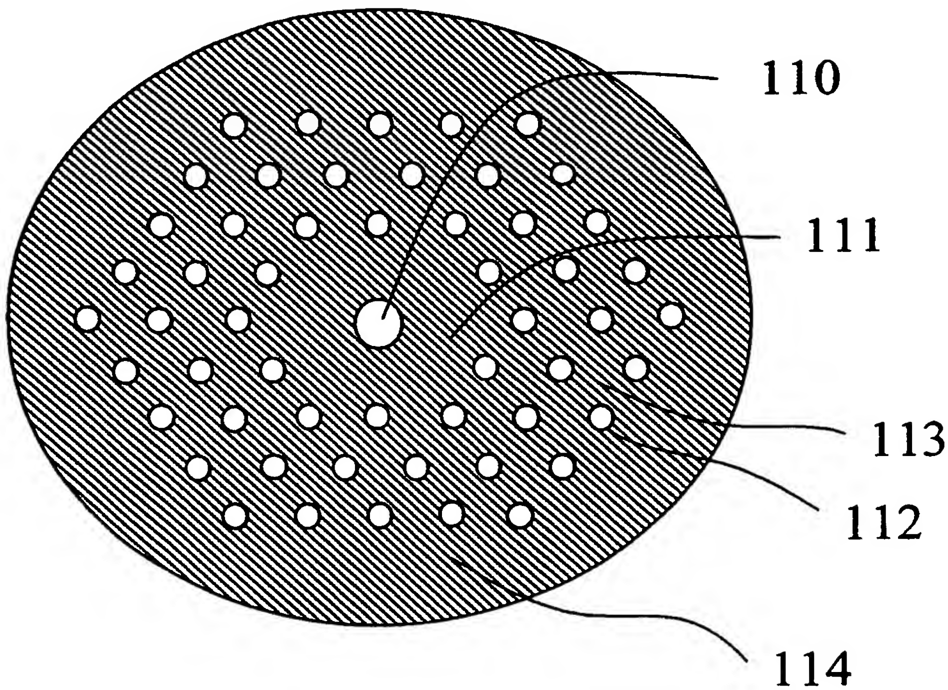


Fig.11b

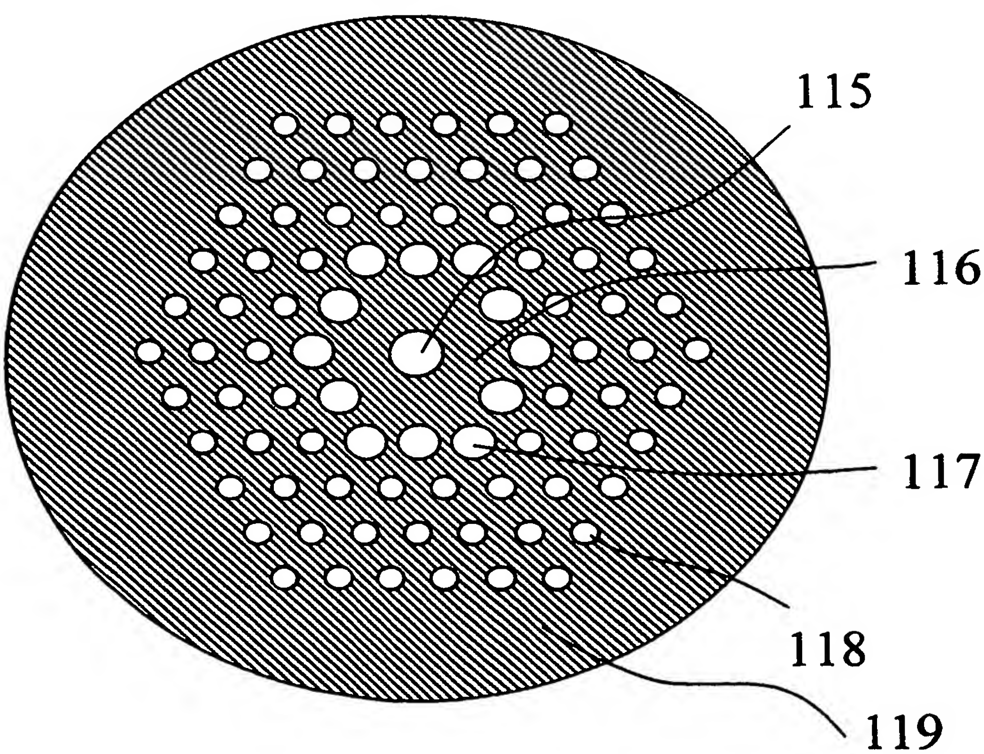


Fig.12

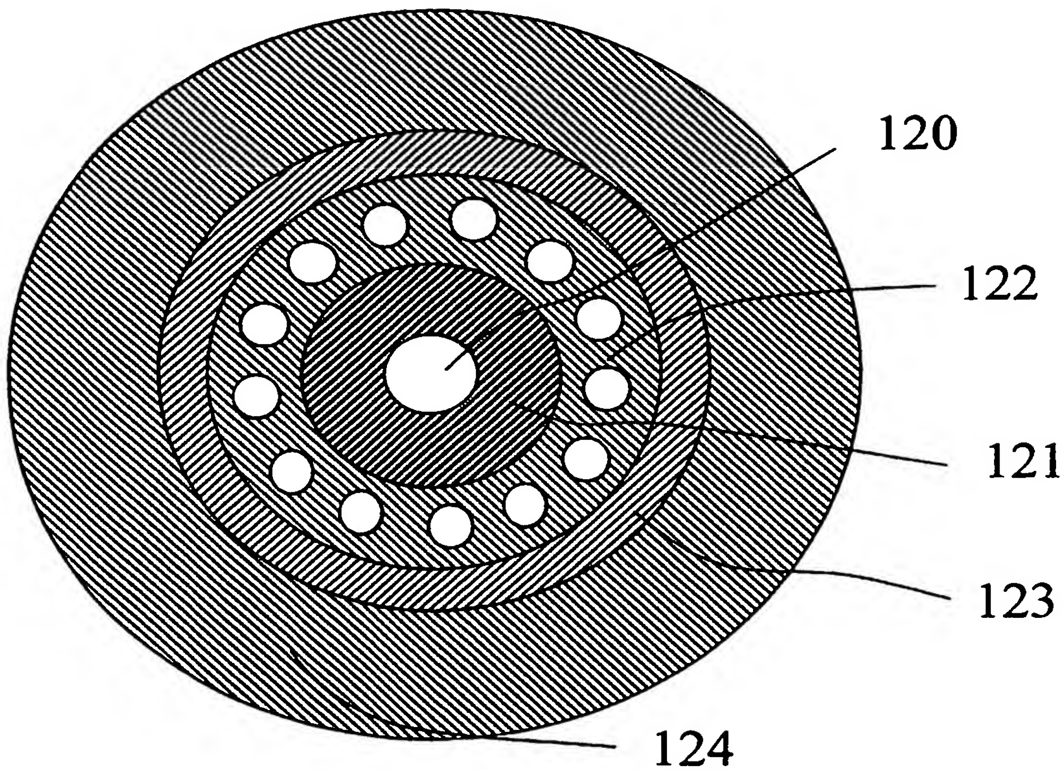


Fig.13

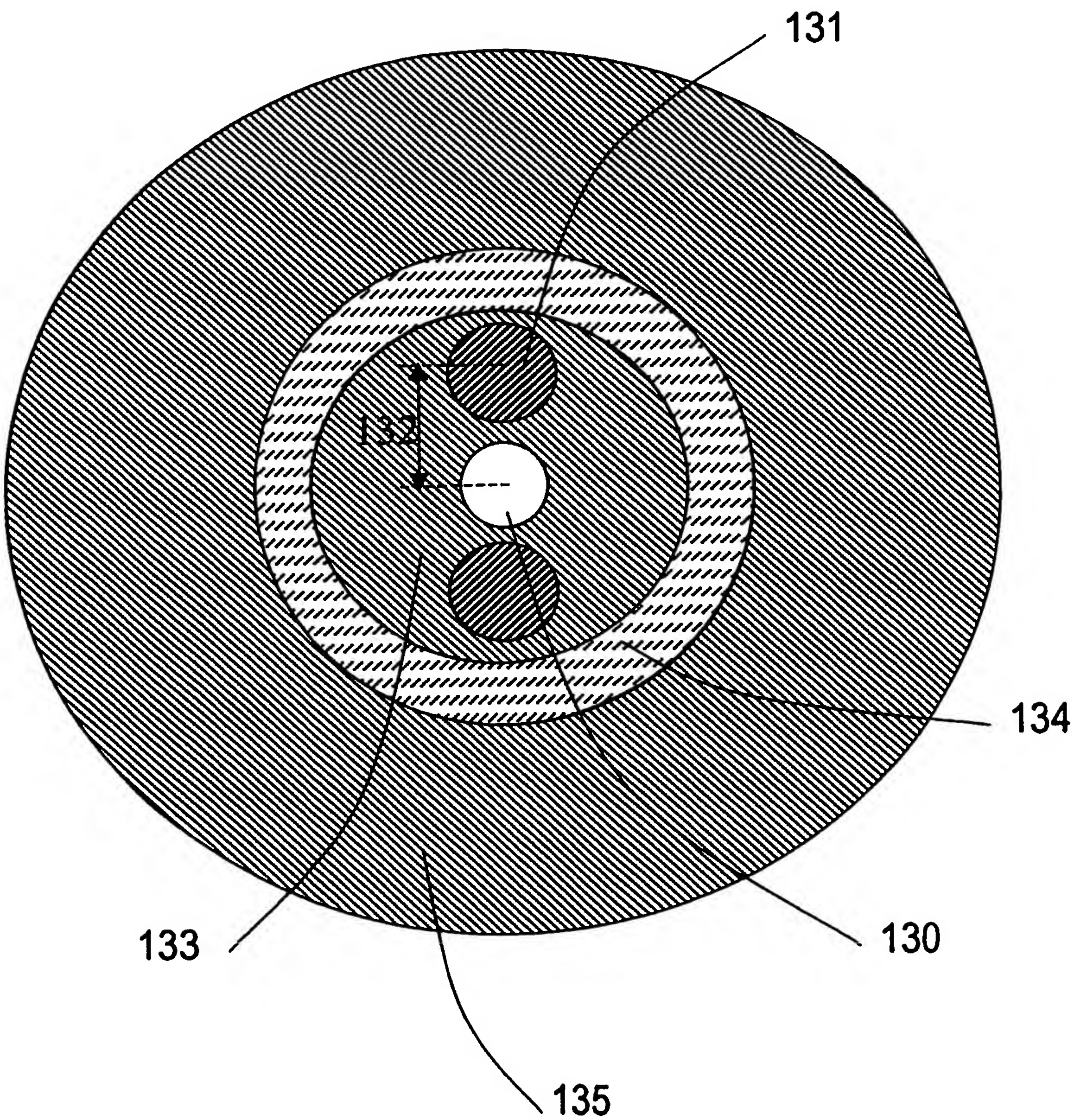


Fig.14

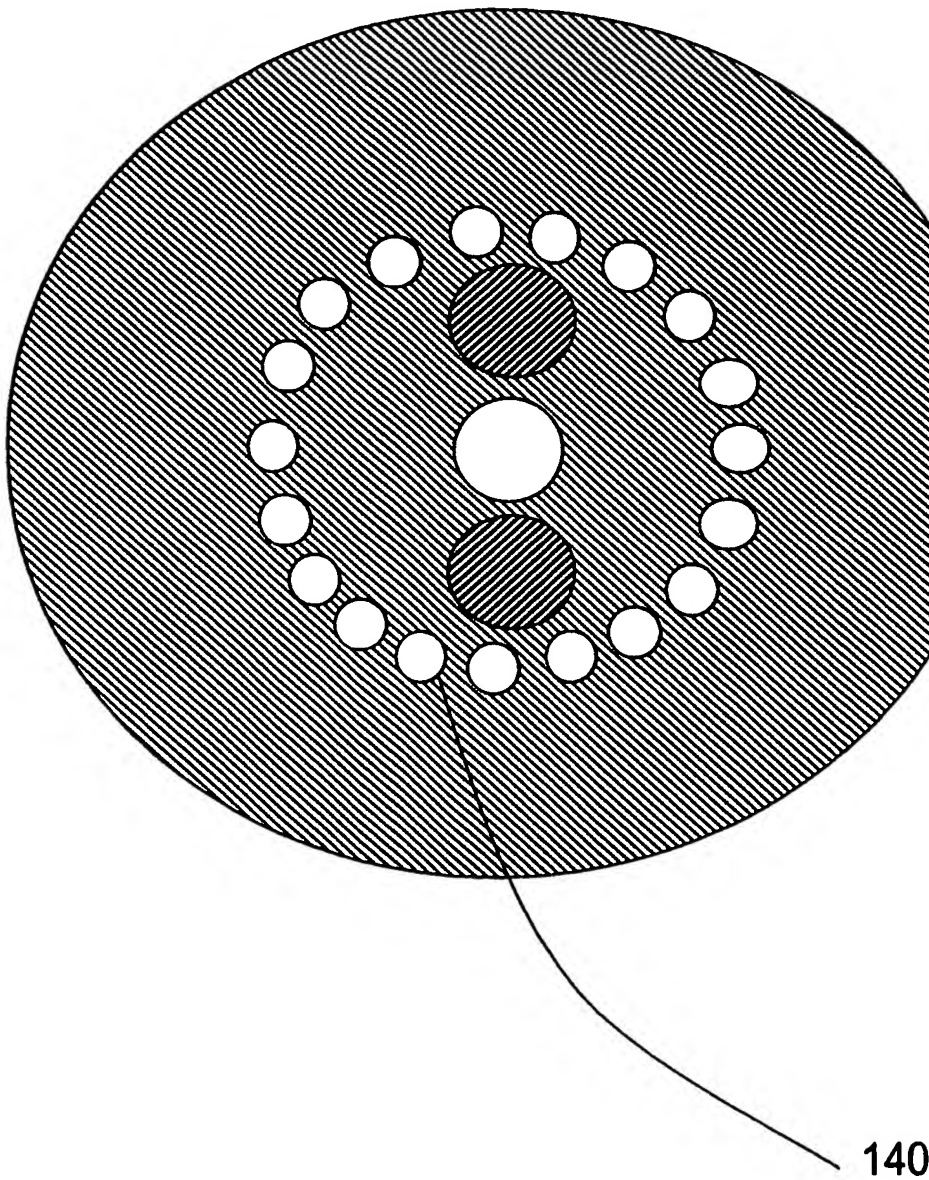


Fig.15

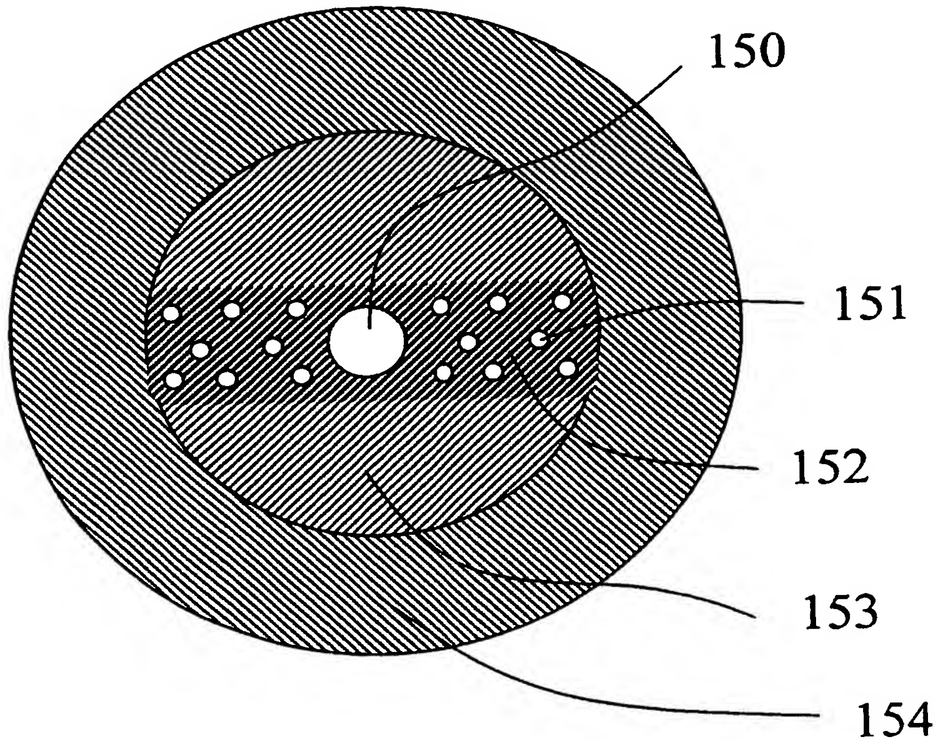


Fig.16

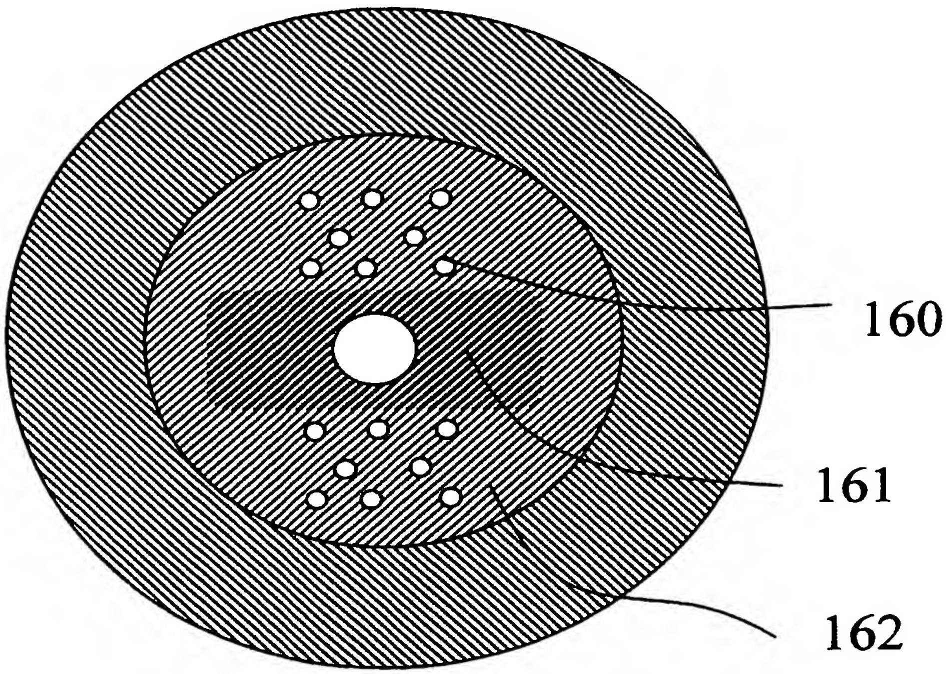


Fig.17

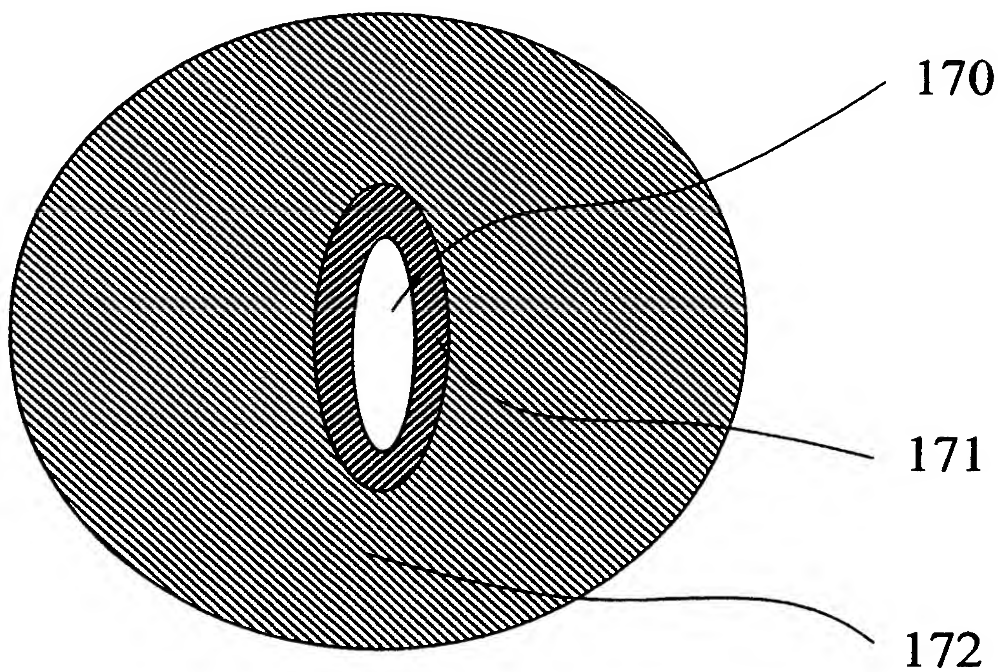


Fig.18

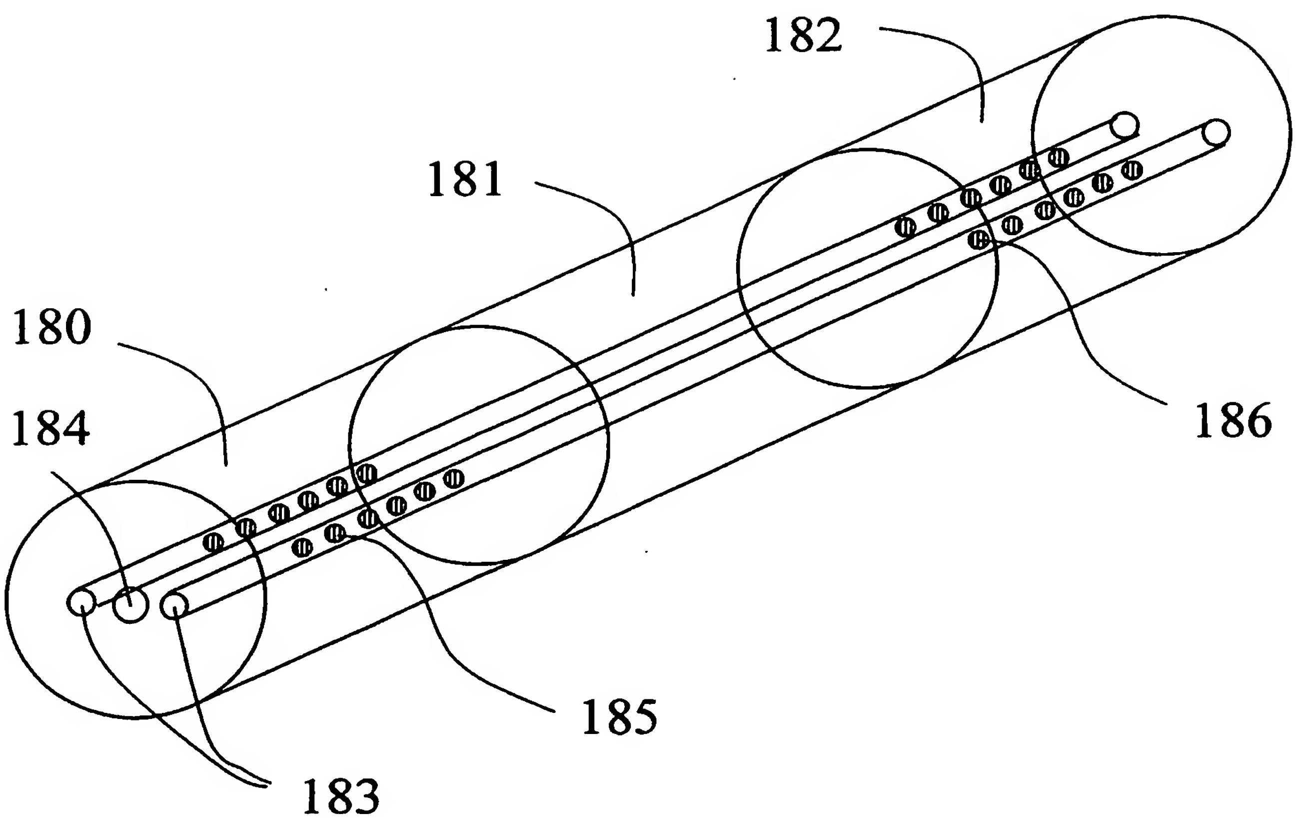


Fig. 19

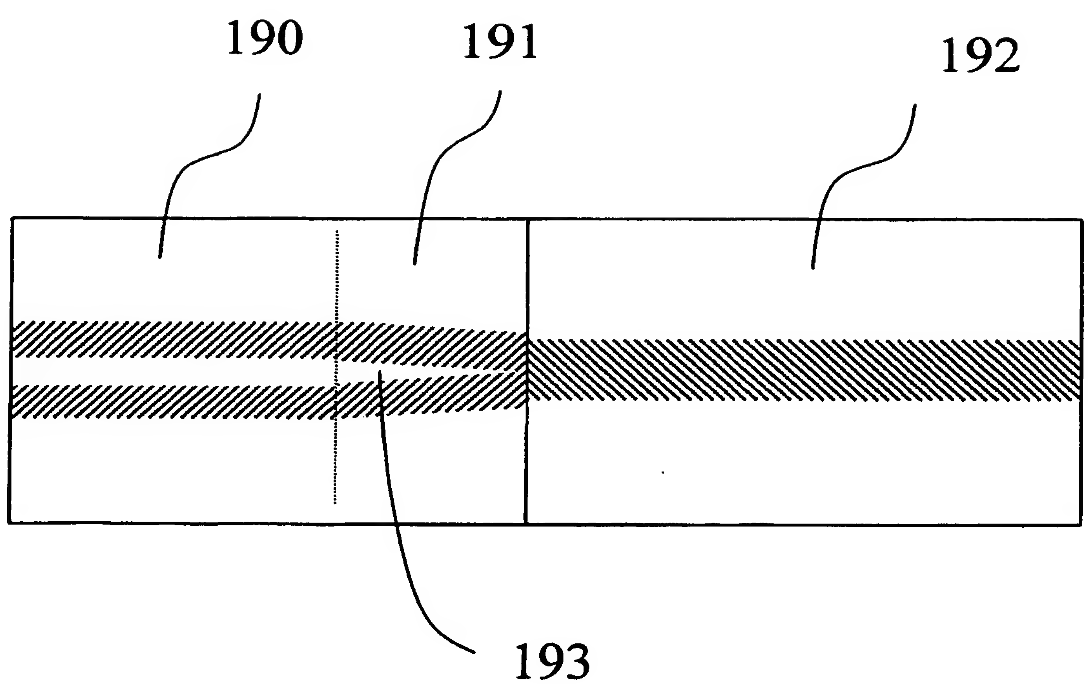


Fig.20

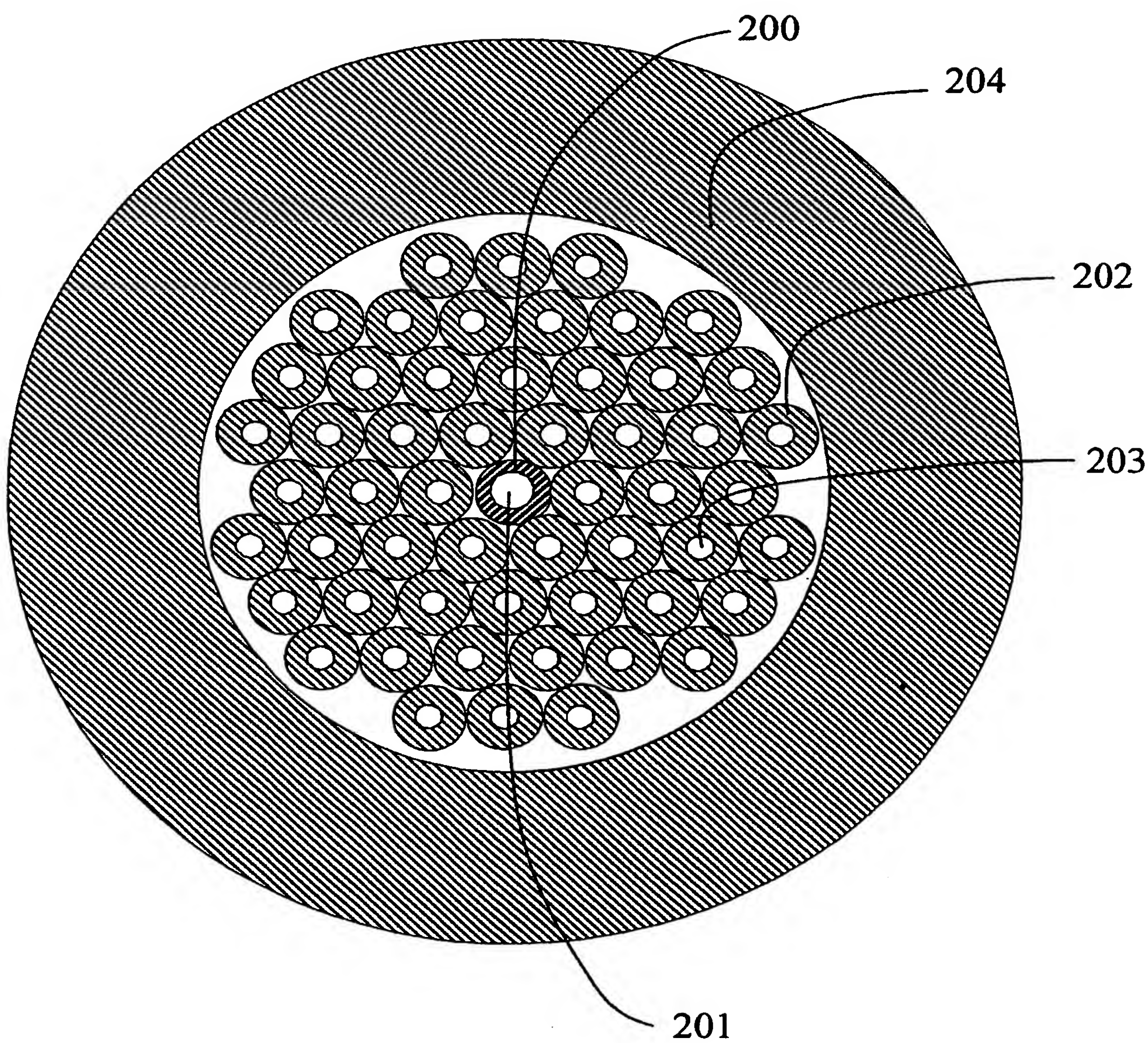


Fig.21

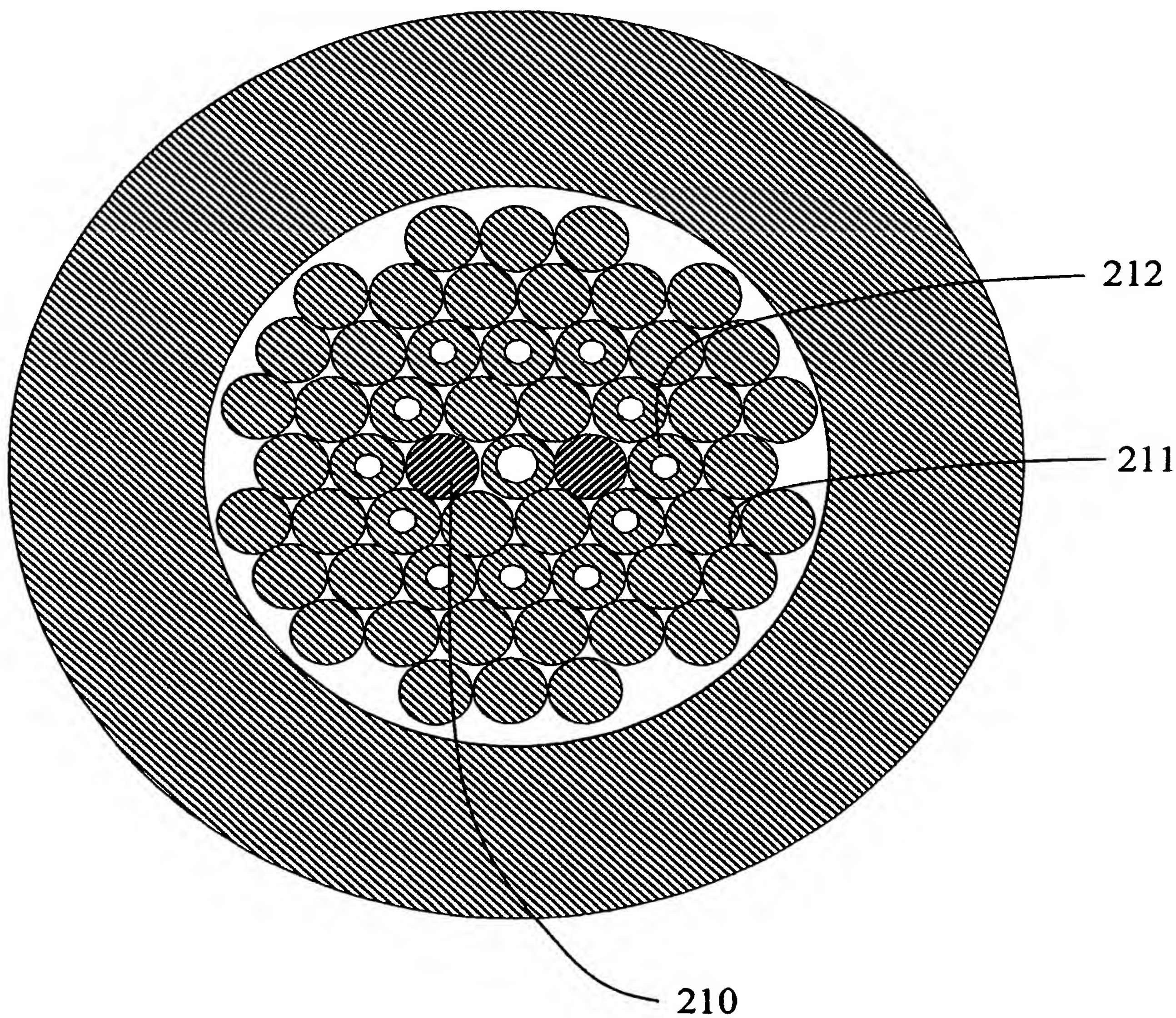


Fig.22